UNIVERSITY OF ALBERTA

Microclimate and geomorphic responses to wildfire in a subarctic upland forest underlain by permafrost

by

Jérôme-Etienne Lesemann ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

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G.P. Kershaw.

G.P. Kershaw (Supervisor)

J.H. England

R.W. Wein

Date: 22 Sept. 1998.

Abstract

A study was undertaken to assess the post-fire microclimate and geomorphic responses of a subarctic upland forest underlain by permafrost. The study site was a simulated transport corridor located near Tulita, NWT. Microclimate data were collected for air and soil temperatures, wind speed, relative humidity, radiation fluxes and snowpack characteristics. Soil cores were used for texture and moisture content analysis. Active layer depth was measured by the probing method. Surface subsidence was assessed using topographic leveling techniques and ground penetrating radar. In burned treatments tree canopy removal and surface albedo lowering led to increases in net radiation and warmer soil temperatures. Post-fire snowpacks were thinner and denser than pre-fire values. Soil moisture decreased after fire. Post-fire increase in active layer depth and seasonal/long term subsidence was inversely proportional to the degree and age of the disturbance. Subsidence and thaw depth were maximal in the trench, right-of-way and burned forest respectively.

Acknowledgments

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Finally, I have to thank my parents and family for their encouragement and support. They have always let me choose my own path and have unconditionally supported my choices from chasing horses to permafrost.

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Chapter 1: Introduction, site descriptions, thesis objectives and thesis outline

Introduction:

A growing body of literature exists concerning permafrost and northern development. The study of environmental disturbances and their effects on permafrost terrains and ecosystems has received growing attention. The main body of literature on this subject was produced during the later part of the 1960's and up to the middle of the 1970's. It coincided and was likely driven by the increase in northern development, the proposals for hydrocarbon development and transport corridors and the numerous northern exploration projects that were initiated during this period. The majority of 'benchmark' literature on the subject was written during this time.

Disturbance studies in the Subarctic have focused on the two main types of perturbations that can affect permafrost areas: anthropogenic disturbances and natural disturbances. During the peak of northern development, it was quickly recognized that the presence of permafrost, and particularly the presence of thaw-susceptible ice-rich substrates, presented unique problems for engineering. Anthropogenic disturbances, such as the construction of roads, pipeline corridors and buildings were studied extensively and much has been learned on the construction and remediation techniques necessary for construction on permafrost terrain (Brown 1970, Wright 1981).

The study of natural disturbances has been ongoing but the body of literature on the subject is much less voluminous than that associated with geotechnical engineering. One obvious reason for this disparity is the periodicity of these naturally occurring events and the logistical complexities associated with northern research. The main focii of natural disturbance studies have been river flooding (Viereck 1973) and wildfires (Hegginbottom 1973, Mackay 1968,1995, Viereck 1982). Although there is widespread literature on forest fires in the Subarctic, most have focused on the biological effects rather than the abiotic/physical effects that also induce biological change. Benchmark studies have been done on the long-term changes in permafrost after the Inuvik, NWT fire of 1968 (Bliss and Wein 1971, Hegginbottom 1973, 1971, Mackay 1970, 1995). These studies constitute the majority of the geomorphic information available on the post-fire response of areas underlain by continuous permafrost. Similar, studies have been carried-out in areas of discontinuous permafrost within Alaska (Hall *et al.* 1978, Racine 1979, Viereck 1982). There is a lack of information concerning the effects (long- and short-term) of wildfires in areas of discontinuous permafrost within Canada, as well as the effects of wildfires on anthropogenic disturbances such as transport corridors.

Previous post-fire investigations in permafrost terrain

Changes in permafrost are mainly the result of microclimatic variations. Degradation and aggradation of the permafrost as well as seasonal active layer depth is largely governed by the temperature at the ground surface and the soil heat flux (Rouse 1982, 1983, Williams 1982, Williams and Smith 1989). Changes in the ground thermal regime will generally result in fluctuations of the active layer, causing an increase of its depth (Brown and Grave 1979, Brown and Péwé 1973, Williams and Smith 1989). The ground thermal regime constitutes a fragile, dynamic balance between vegetation, topography and microclimate.

Effect of burning on microclimatic conditions:

Following a wildfire, the ground thermal regime will be modified by the removal of vegetation. In most cases, the heat from the fire will not generate changes in the permafrost (Viereck 1982, Kershaw and Rouse 1976). This is partly due to the speed at which the fire travels and its brief residence time (Mackay 1995). The burning intensity is directly proportional to the amount and moisture content of fuel available, and this is often scarce in Subarctic environments (Kershaw and Rouse 1976, Liang *et al.* 1991). Consequently, post-fire permafrost terrains will often have decreased surface reflectivity and increased radiation absorption forcing a marked increase in soil temperatures and evaporation rates (Liang *et al.* 1991, Rouse 1976, Rouse and Mills 1977, Haag and Bliss 1974). This can be coupled with a decrease in the relative humidity. Increased air temperatures favour higher rates of evaporation which tend to dry the soil and alter permafrost conditions. The decrease in relative humidity affects the growth of vegetation by retarding its regeneration. Rouse and Mills (1976) found that absorbed solar radiation increased by 15% on burned sites and net long-wave radiation loss increased by a factor of 2.3.

Changes in seasonal thaw depth and surface subsidence

The variation in active layer depth after fire is an index of the change in the permafrost environment (Liang *et al.* 1991, Hegginbottom 1973). Increases in active layer depth have also been associated with the removal of vegetation (Hegginbottom 1973), increased snow accumulations (Nicholson 1978) and the presence of standing or running water (Kerfoot 1973). Often associated with variations of thaw depths is a change in surface morphology. Generally, thermokarst subsidence occurs as a result of the melting of ice-rich, thaw-susceptible permafrost (French 1976, Hegginbottom 1971, Rowe *et al.* 1975, Wein 1975). This melting can be the result of an environmental disturbance (natural or anthropogenic) (Evans *et al.* 1988). It can also result from an increase in the annual amplitude of the temperature at the ground surface, which does not necessarily imply a change in the mean ground temperature (Williams and Smith 1989).

Quantitatively, the amount of thaw subsidence depends on the increase in thaw depth and the amount and distribution of pre-existing ice (French 1976, Williams and Smith 1989). The thawing of ground ice involves a decrease of volume by 9%, followed by an additional volume loss due to drainage of meltwater (Williams 1982). The final settlement will be a function of the effective stress between soil particles (Mackay 1995). Additionally, thermokarst subsidence can be a "self-perpetuating" process where initial ground subsidence allows the entrapment of water which favours thawing to progress deeper into the ground, leading to further subsidence. Rates of subsidence will vary depending on the time since disturbance, soil characteristics (mainly particle size) and the rate at which meltwater is evacuated from the soil. In Inuvik, Hegginbottom (1971) observed a ground subsidence of 33% during the first summer after the fire. Laboratory tests of the same ice-rich permafrost have shown subsidence varying between 40-90% of the original thickness of the frozen material (Mackay 1995). At the SEEDS site, following clearing, total subsidence between 1986 (time of clearing) and 1990 was 31 cm and 57 cm for the ROW and Trench treatments respectively (Nolte 1991).

Effects of snow accumulation on ground temperatures and active layer thickness

Snow has an important influence on ground temperatures because its insulating effect reduces winter heat loss (Nicholson and Grandberg 1973). The insulation is proportional to the thickness of the snowpack as well as its thermal conductivity, which varies with depth and density (Kershaw 1991). Shallow snow accumulations offer less insulation, contributing to the maintenance and/or growth of permafrost (Mackay 1995). Other factors also influence ground temperature such as substrate texture, soil moisture, vegetation cover, aspect and relief. There is a close relationship between snow depth and relief and between snow depth and vegetation (Nicholson and Grandberg 1973). Furthermore, dense vegetation will create a barrier to winds that can scour and redistribute snow (Kershaw 1991, Rouse 1982, 1983), enhancing the insulation of the ground where snow accumulates (Kind 1981). However, snow accumulation under tree cover is mitigated by retention by tree branches and shrubs which can reduce the snow cover on the ground, thus lowering winter soil temperatures (Viereck 1965, 1973 from Tyrtikov 1959).

Influence of vegetation cover on permafrost distribution:

Vegetation influences active layer depth by changing the net radiation and the convection-conduction relations of the surface boundary. Evaporation and transpiration cause a cooling of the organic layers due to heat dissipation (Brown 1983). Soil surface temperatures, subsequent to the removal of a tree canopy can increase by 60 to 70%. Even after 25 years, surface temperatures can remain 30 to 40% warmer than in unburned environments (Kershaw and Rouse 1976). The thawing of the upper permafrost can compensate for the release of moisture that is favourable to the regeneration of plants (Mackay 1995). It is speculated that, as the vegetation regenerates, the active layer should become progressively thinner until it eventually reaches its pre-burn thickness (Viereck 1973, 1982). Mackay (1995) has observed that 25 years after the Inuvik fire, permafrost aggraded causing ground uplift as a result of the aggradation of ice.

Site description:

The study site was the *Studies of the Environmental Effects of Disturbances in the Subarctic* (SEEDS) research site (64° 58' N, 125° 36' W), located approximately 10 km north of Tulita (Fort-Norman), NWT (Figure 1-1). The SEEDS site was established in 1985 and consisted of a simulation of a northern transport corridor (pipeline, winter road, high-tension electrical line, etc.). The simulated transport corridor was a hand-cleared, 690 m-long S-shaped right-of-way (ROW) in a *Picea mariana* stand that burned in June 1995. The north-south oriented clearings were numbered as ROWs 1, 2 and 3 from west to east, and the connecting parts were called North and South links (Figure 1-2). In 1985, ROWs 1 and 3 as well as the North link were cleared, and in 1986 ROW 2 and the South link were added. A buried pipeline was simulated by excavating a 553 m-long, 2 m-wide and 50 cm-deep trench which was back-filled with the excavated mineral and organic material (Kershaw 1988 b). The main objectives of the SEEDS project were to collect biotic and abiotic data prior to disturbance and to monitor the effects of such a disturbance. Additionally, the site was used to test and monitor various long-term reclamation treatments (Kershaw,1988 a). In order to assess the impacts of various types of disturbances and the influence of natural environmental changes, monitoring programs were carried out in both disturbed (trenches and ROWs) and undisturbed areas that were used as controls (uncleared forest between each ROW) (Figure 1-2). These include a relatively complete, 11-year record of soil and permafrost characteristics (moisture/ice contents, particle size, active layer thickness) as well as microclimatic characteristics (Kershaw, unpublished data). Various disturbance studies have been carried out at the site and they include work on the ecological effects of crude oil spills (Seburn 1993, Seburn *et al.* 1996, Seburn and Kershaw 1997), and permafrost degradation as a result of anthropogenic disturbance (Gallinger 1990, Gallinger and Kershaw 1988, Nolte 1990, Nolte and Kershaw 1998).

In 1995, a wildfire swept over the SEEDS area burning over 58 500 ha. This provided an ideal opportunity to assess the fire-induced changes in microclimatic and permafrost conditions, in an area of discontinuous permafrost. These new objectives will be addressed in this thesis.

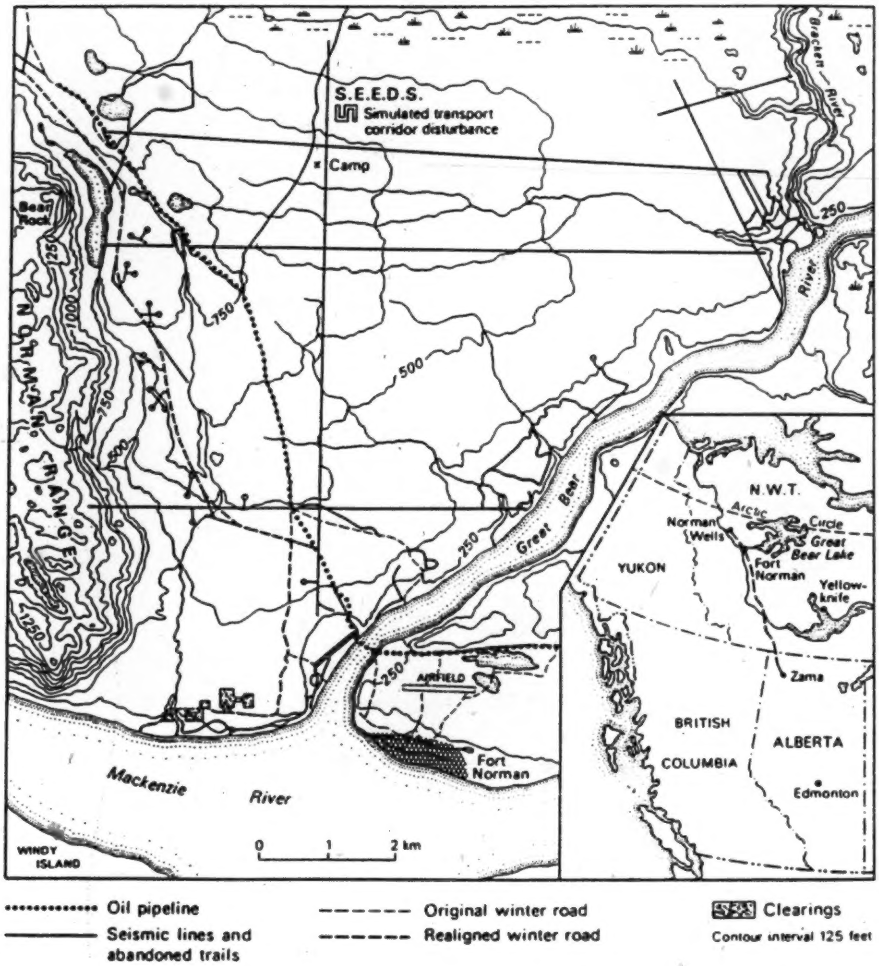

Figure 1-1: Location map of the S.E.E.D.S (*Studies of the Environmental Effects of Disturbances in the Subarctic*) research site (Kershaw 1991). The hamlet of Fort-Norman is now called Tulita ("Where the waters meet").

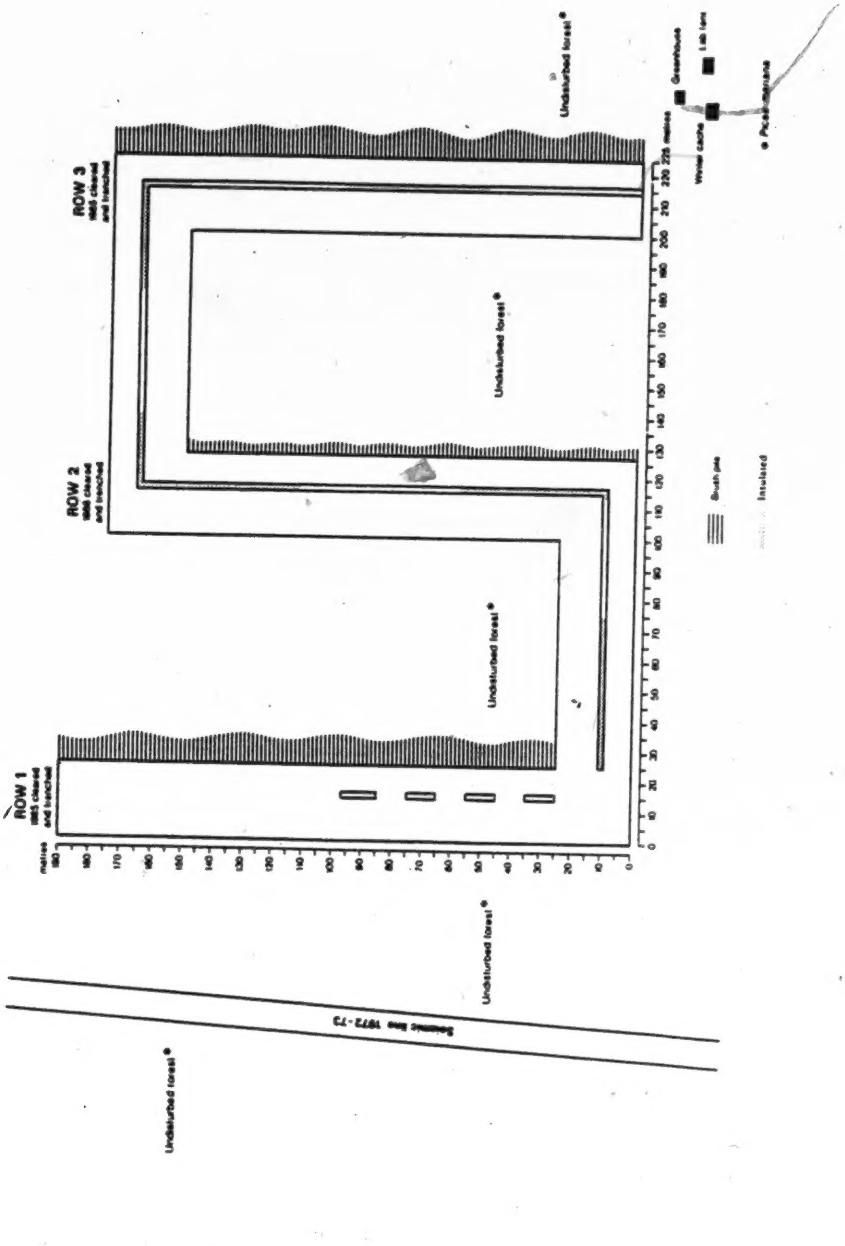

Figure 1-2: *S.E.E.D.S.* simulated transport corridor in 1986-1987. Areas of *Undisturbed forest* are now referred to as *burned forest.* Kershaw (1986).

Geology and soils

The SEEDS site is situated within an area of flat, to gently sloping glacio-lacustrine plain. Local relief is generally by hummocky micro-relief (Reid 1974, Zoltai and Tarnocai 1975). The regional geology consists of Devonian dolomitic and limestone breccias with depths to bedrock of over 5m (Hughes *et al.* 1973, MacInnes *et al.* 1989, Reid 1974). A thick (~10 m) accumulation of deltaic sand and silt were deposited in the area by the extensive Glacial Lake Mackenzie during the late Wisconsinan (Smith 1990).

Until the 1970's the soils of the Mackenzie valley remained unclassified (Pettapiece 1975). Evans *et al.* (1988), Kershaw and Evans (1986) classified the pre-fire soils of the SEEDS site as Gleysolic Turbic Cryosols with organic soil horizons 15-30 cm thick. These organic horizons sustain a layer of live moss and lichen three to five cm thick. Soil pH was found to decrease with depth, reflecting the acidic nature of the peat. The soil texture was described as silty loam, with an average clay fraction of 20% and a fine sand fraction varying from 4% to 55% (Kershaw and Evans 1986). A discontinuous coarse sand/ pebble layer is present within the glaciolacustrine sequence between 132 and 225 cm below the surface.

Permafrost is widespread at the SEEDS site (Kay *et al.* 1983, MacInnes *et al.* 1989). According to Brown (1970) and Nixon *et al.* (1983) the site falls within an area where approximately 85% of the terrain is underlain by discontinuous permafrost. Permafrost thickness does not exceed 50 m (Judge 1973).

Climate:

The climate of SEEDS has been classified as Subhumid High Boreal (Ecoregions Working Group, 1989). The Tulita meteorological record shows that winters tend to be long with temperatures reaching -20°C or less during five months of the year. The summers are short with only three months averaging over 10°C (Atmospheric Environment Service 1982). Annual precipitation is relatively low (mean annual precipitation is 460 mm), the majority of which accumulates in winter as light snowfalls. Snowcover is generally present from late October to early May. However, 45% to 55% of the total precipitation occurs between June and September, when rainstorms are frequent. The thaw season averages 95 to 125 days and extends from May to September.

Vegetation:

Prior to the 1995 fire, a boreal forest community dominated, by larch (*Larix laricina*) and black spruce (*Picea mariana*) approximately 300 years old (Kershaw 1985, 1986). The open-canopied forest ranged in height from 4-6 m. Tree morphology was characterized by single crown or small groups of trees with crown cover of approximately 8% (trees greater than 2 m in height) (Kershaw 1988, Schotte 1988). The dominant shrub species were the little tree willow *Salix arbusculoides*, shrubby cinquefoil (*Potentilla fruticosa*) and dwarf birch *(Betula glandulosa)*. Understory vegetation consisted mainly of Labrador tea (*Ledum groenlandicum*), bearberry (*Arctostaphylos rubra*), bog cranberry (*Vaccinium vitis-idaea*), bog blueberry (*Vaccinium uliginosum*) and crowberry (*Empetrum nigrum*). Non-vascular species provided, with exception of the trench, an almost continuous cover on the ground surface. Common moss species included the feather moss (*Hylocomnium splendens*) as well as *Tomenthypnum nitens* and *Aulacomnium palustre*. Lichen species were dominated by the genus *Cladonia* (Kershaw L. 1988).

The complete burning of the black spruce, the shrubby species, and part of the understory greatly altered the vegetation. Most of the black spruce were killed and only burned trees were left standing. Tree crown density was reduced to nil. The understory was not completely consumed during the fire and regrowth has been ongoing since 1995. In post-fire conditions, there has been a proliferation of the shrubby species (*S. arbusculoides*). The mean total vegetation cover in the post-fire control treatment was 115%. The dominant species were *Cladina mitis* (29% cover) and *Picea mariana* (18% cover). Other dominant species included *Vaccinium vitis-idaea*, *V. uliginosum*, *Arctostaphylos rubra*, *Tomenthypnum nitens*, *Aulacomnium palustre*, *Salix mirtilifolia*, *Ledum groenlandicum*. *Betula glandulosa*, *and Helyocomnium splendens*. Acrocarpous and pleurocarpous bryophytes accounted for 8% and 2% cover respectively (Kershaw, unpublished data)

In the burned treatments, vegetation was only present below 30 cm. Mean total cover in the burned forest was 3% with no species contributing more than 1% to total cover. On the burned ROW, mean total cover was 18%. This was dominated by non-vascular species such as *Marchantia polymorpha*, (8% cover) and acrocarpous bryophytes (7% cover). The prevalent vascular species was *Epilobium angustifolium* (1% cover) (Kershaw, unpublished data).

In 1985 and 1987 mean cover in the undisturbed forest at the SEEDS site was 148% and 144% respectively. *P. mariana* cover was 18% in 1985 and 17% in 1987 (Kershaw 1988). The post-fire control treatment had a tree stem density of 1.11 stems m^{-2} (Kershaw, unpublished data) which was comparable to the pre-fire stem density of 1.06 stems m^{-2} from the SEEDS treatments (Schotte 1988). Mean cover in the post-fire control was less than in the pre-fire control. However, *P. mariana* cover was comparable, making the post-fire control an adequate analogue of pre-fire conditions.

Structure of thesis and research objectives:

The thesis has been subdivided into five chapters. Chapters 1 and 5 are introductory and concluding chapters respectively and Chapters 2, 3 and 4 deal with the microclimatic changes accompanying wildfire, the changes in soil characteristics and active layer depths and, the geomorphic response of a fire-affected permafrost terrain respectively.

Chapter 1 is an **introduction** to the thesis structure as well as an introduction to the subject matters explored in chapters 2, 3 and 4. It contains a brief literature review of permafrost research and of the effects of disturbances on permafrost-affected terrains. Particular emphasis is placed on the effects of wildfires in Subarctic regions. Additionally, a general overview of the SEEDS research site and project has been outlined and the general site attributes of the research area are described.

Chapter 2 has been titled "**Microclimatic responses to a Subarctic upland forest following wildfire**". The main objectives of this chapter are:

i) Perform a qualitative comparison of the post-fire microclimate conditions for four surface treatments on the SEEDS site (Right-of-Way, Trench, Burned forest and Control).

ii) Quantify the changes in the microclimate factors that are determinant in the energy balance of the surface.

iii) Compare the values obtained for these parameters for each of the SEEDS treatments in post-fire conditions.

Chapter 3 has been titled "**Soil properties and thaw depths following wildfire in a Subarctic upland forest and on a simulated transport corridor**". The objectives are:

i) Quantify the post-fire changes in thaw depths and soil moisture contents for the various SEEDS treatments.

ii) Compare the pre- vs. post-fire thaw depths and moisture content for the SEEDS treatments.

Chapter 4 has been titled **"Thermokarst subsidence and seasonal /long-term terrain modifications following fire and anthropogenic disturbance"**. It is complementary to the two previous chapters and incorporates these data in a geomorphic analysis. The objectives are:

i) Compare and quantify the 1997 seasonal surface change in each SEEDS treatment.
ii) Determine the degree of total surface subsidence resulting from burning and /or clearing since the initial clearing (1986) and the last topographic survey (1990).

Chapter 5 **"Conclusions"**, contains a brief summary of the thesis.

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Chapter 2: Microclimatic responses to a Subarctic upland forest following wildfire.

Introduction:

Changes in permafrost mainly result from the modification of microclimatic conditions and the heat exchange at the ground surface. Degradation or aggradation of permafrost as well as seasonal development of the active layer depend on these ground surface conditions (Rouse 1982, 1983; Williams & Smith 1989). In turn, this energy exchange is greatly affected by the nature of the ground surface, and any perturbations of surface conditions will have direct repercussions on the ground thermal regime (Brown and Grave 1975; Brown and Péwé 1973; Williams and Smith 1989).

Wildfires are one type of disturbance which cause changes in the ground thermal regime. During the actual burning, little modification of permafrost conditions occurs (Brown 1983). The immediate effects of burning are negligible because the direct input of heat to the soil is small because both mineral and organic layers are poor conductors. Van Wagner (1970), found temperature gradients of 10°C mm^{-1} in mineral soil and 28°C mm^{-1} in partly decayed organic material. A temporary surface temperature of 450°C would therefore have little effect below 5 cm depth (Brown 1983). Post-fire modifications of permafrost occur in the months and years following burning, as the surface energy balance is changed. The degree to which permafrost is modified largely depends on whether the fire burns only the tree crowns, or the trees and the undergrowth to the ground surface, or whether the surface organic matter is partially or completely destroyed (Brown 1983). Where post-fire vegetation recovers rapidly, the impacts on permafrost can be mitigated by the shading effect of new vegetation (Tsytovich 1975). Additionally, the albedo will increase as vegetation recovery progresses.

Objectives:

The objectives of this study were to:

i) Perform a qualitative description of the post-fire microclimate conditions for four surface treatments on the SEEDS site (Right-of-Way, Trench, Burned forest and Control).

ii) Quantify and compare the changes in microclimate conditions between burned treatments and control.

iii) Determine the importance of the radiation budget components in modifying the surface energy exchanges in burned and unburned surfaces.

Factors affecting permafrost and the ground thermal regime

-Pre-fire (undisturbed) energy exchanges and permafrost equilibrium:

In undisturbed, pre-fire conditions, the thermal state of permafrost is in equilibrium with the prevailing microclimate. In areas of discontinuous permafrost, the "summer" period (following snowmelt) is characterised by thawing of the upper layer of the ground. This thawed material - the active layer- will vary in thickness according to the amplitude of summer temperatures. Active layer development is not restricted to areas of discontinuous permafrost, as it is also present in areas of continuous permafrost but its thickness can be much less.

The seasonal development of the active layer is determined by the temperature regime at the ground surface, the thermal properties of the ground and the water/ice content of the active layer. Atmospheric mass and energy flows and the geothermal heat flux are boundary conditions accounting for the equilibrium between permafrost and its surrounding environment, with the vegetation canopy, snowcover and the surface organic layer acting as buffers between the atmosphere and the mineral soil (Riseborough 1985).

-Effects of vegetation on the radiation budget and the ground thermal regime:

The importance of vegetation in controlling the energy exchanges of the ground can be divided into two categories, according to vegetation architecture: the overstory vegetation (tree canopy) and the bryophyte layer at the ground surface.

In forested areas, the physical characteristics of the canopy are determining factors in the energy exchanges between forest-atmosphere-permafrost. Trees intercept a large portion of the daily solar radiation, thereby reducing the net solar flux below the canopy (Munn *et al.* 1978, Luthin and Guymon 1974, Brown and Pewe 1973, Haag and Bliss 1974 a). Some of the short-wave incoming radiation is reflected back to the atmosphere as a function of the albedo of the tree crowns or leaves (Lafleur and Adams 1986). Another portion of this incoming radiation is absorbed by the canopy. At the same time, trees act as a source of long-wave radiation as the absorbed heat is re-radiated to the atmosphere as well as towards the ground. Trees also affect air temperatures near the ground by reducing wind flow within and below the canopy (Haag and Bliss 1974 a). The impeded wind flow cannot dissipate sensible heat as readily as open areas and thus promotes higher air temperatures. Secondary roles also include the interception of rain and transpiration by the canopy. This affects the ground thermal regime by modifying the thermal conductivity of the soil and the albedo of the organic layer as a function of the soil moisture contents.

The surface organic layer is often referred to as a buffer layer between the near-surface soil energy exchanges and atmospheric inputs of energy. Three factors cited for this are: *i)* the low conductivity of organic soils relative to mineral soil, *ii)* the effect of the seasonal variation in the moisture content of the organic soil on its conductivity and, *iii)* the seasonal evaporative regime of the surface, as controlled by climatic factors (Luthin and Guymon 1974, Fitzgibbon 1981 from Riseborough 1985). Because of these buffering characteristics, the organic (moss and lichens) layer has been credited with the persistence of permafrost in the southern margin of the discontinuous permafrost zone. Nakano and Brown (1972) demonstrated the importance of the properties of the surface organic layer to the ground thermal regime using a computer model of the thermal regime at Barrow, Alaska. They concluded that the thickness and the moisture content affecting the latent heat exchange of the organic layer exerted the greatest influence on the progression of the frost line through the soil. A similar simulation by Ng and Miller (1977) indicated that the thermal conductivity of the surface layer was the most sensitive parameter, while organic layer thickness was less important than some parameters (e.g. albedo) related to the energy balance of the surface.

-Effects of snowpack characteristics on the ground thermal regime:

Snow has an important influence on ground temperatures because of its insulating effect that reduces winter heat loss (Nicholson and Grandberg 1973). The effectiveness of the insulation is proportional to the thickness of the snowpack as well as its thermal conductivity, which varies with snow density (Kershaw 1991). Shallow snow accumulations offer little insulation, contributing to the maintenance and/or growth of permafrost (Mackay 1995). Additionally, tree cover has a direct effect on the depth and duration of the snowpack (Kershaw 1991, Rouse 1982, Kind 1981, Brown and Pewe 1973). Dense vegetative cover will create a barrier to winds that scour and redistribute snow accumulations (Kershaw 1991, Rouse 1982, 1983). Additionally, these barriers will promote the deposition of wind-transported snow, enhancing the insulation of the ground (Kind 1981). However, snow accumulation under tree cover is mitigated by the retention effect of tree branches and shrubs which can reduce the snow cover on the ground, thus lowering soil temperatures.

-Post-fire energy exchanges and effects on permafrost equilibrium::

It is generally agreed that post-fire permafrost experience a deepening of the active layer as a result of the disruption of the thermal equilibrium. The partial and/or complete removal of both the overstory vegetation and the surface organic layer lead to increases in the amount of energy penetrating the ground and thus lead to active layer deepening. The removal of the trees by fire eliminates their role as interceptors of incoming radiation. This leads to increases in the net solar flux at the surface as short-wave radiation is no longer reflected by tree crowns and long-wave radiation cannot be absorbed by the canopy. Even if the surface organic cover is not completely removed by fire, the blackening of the surface dramatically lowers surface albedo. This leads to an increase in the absorption of short-wave radiation resulting in increased surface temperatures. Changes in the albedo of burned surfaces have been reported, but consistency of values within a particular cover type are difficult to obtain due to variations in surface moisture contents at the time of observation (Brown 1983). For this reason, specific values of albedo are not available. Nonetheless, there seems to be an agreement that albedos of burned surfaces vary between 5-15%. Early work by Jackson (1959) and Davies (1962) reported values of 9% in areas of burned spruce-lichen woodland. In burned lichen-tundra, the post-fire albedo has been observed to vary between 7% (Petzold and Rencz 1975, Rouse and Mills 1976) and 15% (Rouse and Mills 1976). These post-fire values constitute differences of 50%-400% over the albedos of similar unburned surfaces (Petzold and Rencz 1975, Rouse and Mills 1976, Oke 1987). Kershaw *et al.* (1975) reported a rapid post-fire drop in albedo from 20% to 5%, thus giving a fresh burn the lowest albedo of any terrestrial surface. Canopy removal and increases in albedo can lead to increases in soil and surface tmperatures. Soil surface temperatures have been reported to increase by 60-70% subsequent to canopy removal. Even after 25 years, surface temperatures can remain 30-40% warmer than in unburned environments (Kershaw and Rouse 1976).

Another consequence of lowering albedo is an increase in net radiation over freshly burned surfaces (Kershaw *et al.* 1975, Haag and Bliss 1974 b). However, contradictory results have been reported by Kershaw and Rouse (1976) where burning led to a reduction in summertime net radiation of 15%-19% over burned surfaces of various ages (0, 1, 2, 24 and 81 yr.). This was attributed to differential surface heating between sites of different ages, which increased the amount of outgoing long-wave radiation. These authors noted an immediate decrease in net radiation of 20% which remained at least 10% lower than unburned surfaces after 50 years. They concluded that the low albedo of freshly burned surfaces does not necessarily lead to an increase in net radiation. Rouse and Mills (1976) also found that net radiation decreased by 11% over burned areas as a result of greater long-wave loss offsetting the increased solar radiation absorption.

Finally, tree removal affects the distribution and characteristics of the snowpack. Open burned areas allow for greater snow erosion by unchecked winds. This leads to thinner, denser snowpacks that favour frost penetration to deeper depths than in undisturbed areas. Consequently, snowpack thinning can lead to colder winter time soil temperatures that may partially offset the summertime deepening of the active layer.

Methods:

Microclimate

Microclimate stations and sensors were re-installed in 1996 by Dr. Kershaw and raw data were extracted from the data archive for analysis here. The initial installations were placed on site in 1985, 10 years prior to the 1995 wildfire.

Microclimate data were collected at four locations within and adjacent to the SEEDS site: 1) burned forest, 2) burned ROW, 3) burned trench and 4) control. All SEEDS treatments were instrumented from 1986-1995 when a wildfire destroyed most of the equipment. In 1996, new stations were erected and data collection has been ongoing since. At each station, sensors monitored soil and air temperatures, wind speeds, relative humidity, precipitation and incoming solar radiation throughout the year. Additionally, "seasonal" sensors were installed during the spring and summer months. In 1997, these were used to measure net radiation, soil moisture and outgoing short-wave radiation. Data were collected and stored on microloggers.

Soil temperatures were measured using 44-gauge, type-T (copper-constantan) thermocouples, made according to Johnston (1973) and attached to a 25 mm diameter wooden dowel. Thermocouples were positioned at depths of 5 cm, 10 cm, 50 cm, 150 cm and 200 cm. This setup was used at the trench, ROW and control stations. Air temperatures at +50 cm and +150 cm were measured with thermistors installed in the relative humidity probes (see below).

Incoming and outgoing short-wave (solar) radiation was measured with LI-COR (model *LI200S-L*) pyranometers installed at a height of 150 cm on each station. Outgoing short-wave radiation sensors were inverted so that the sensor head was oriented towards the ground surface.

Net radiation was measured with *Q7* (Radiation and Energy Balance Systems Inc.) net radiometers. As was the case with the measurement of outgoing short-wave radiation, extreme care was taken to ensure that the surface below the sensors was not disturbed during installation and data collection. All the sensors measuring energy fluxes were installed within or below the canopy. No instruments were deployed above the canopy height. Outgoing long-wave radiation was calculated from surface temperatures using equation (4). Finally, incoming long wave radiation was obtained by calculating the residual value from equations (1) and (2).

At each station, wind speed was measured at two standard heights: 150 cm and 300 cm using MET-ONE anemometers with a programmed offset of 0.447 m^{-1}. Additionally, *Campbell Scientific* (Model 207F) and Vaisala (Model HMP 35C) temperature and relative humidity probes were installed at heights of 50 cm and 150 cm. The data were recorded on a combination of *Campbell Scientific* automated dataloggers (Models CR10X and 21X with attached memory modules). These units were powered by 12 V batteries that were kept charged continuously with solar panels. Loggers and power supplies were housed in protective shelters.

Snow course measurements:

Snow sampling was performed during the week of 17 February 1997. Sampling sites were established in 1985 with pre-fire results reported in Kershaw (1991). The same sites were used in 1997 since they were selected to provide representative samples from each SEEDS treatments (Figure 2-1). Additionally, 60 sites were randomly sampled in the control treatment. Leading edge burned forest sites were within the burned forest, less than 15 m from the ROW edge.

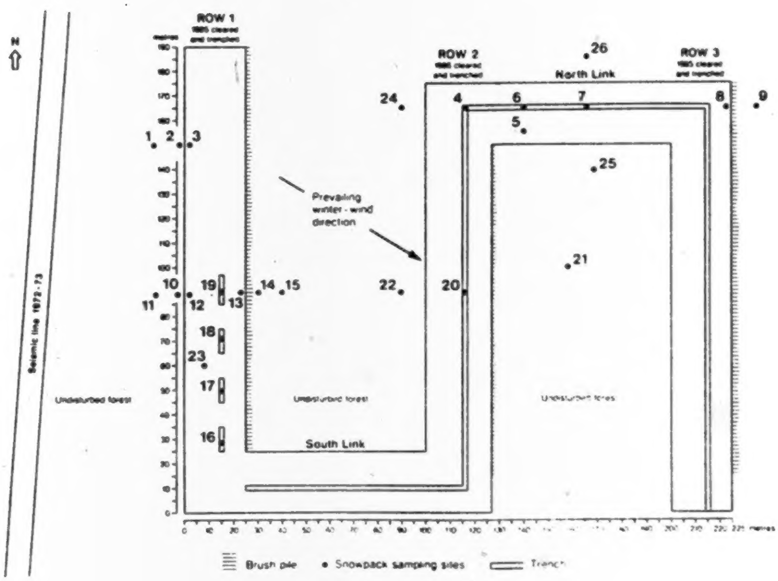

Figure 2-1: Snowpack sampling sites on the simulated transport corridor, SEEDS, Tulita, NWT. Sampling sites have been categorized as burned forest (sites 1, 2, 10, 11, 21, 22, 24 and 26), transport corridor (sites 3, 4, 5, 6, 7, 8, 12, 13, 16, 17, 18, 19, 20 and 23) and leading edge of forest (sites 9, 14, 15 and 25) (Kershaw 1991).

At each site, 5 snow core samples were extracted with an Adirondack snow corer. The sampling technique used is outlined by Adams and Barr (1974). Analysis was based primarily on the depth and density data derived from this data set. The major site differences resulting from exposure to wind were noted. During the winter, prevailing wind direction was from the west-northwest striking the three 150-m long ROWs at an oblique angle (Figure 2-1). The two 125-m long east-west corridor segments were positioned at approximately 30° to the prevailing winter wind direction (Kershaw 1991).

Data analysis;

The air temperature data were analysed by using a "thawing degree index" (TDI) and a "freezing degree index" (FDI). This index is the sum of all positive (TDI) and negative (FDI) air temperatures during the measurement period. The index was used as a means of comparing the differences in cumulative air temperatures over each treatment. It was also an indicator of the degree of post-fire change in surface conditions that lead to changes in air temperatures.

The microclimate data were processed using the Microsoft Excel spreadsheet program. Statistical analysis of the data was performed with the Jandel SigmaStat software package. Figures and tables were produced by using a combination of Excel and Jandel SigmaPlot software packages.

Theory:

-Components of the radiation budget.

The radiation balance at the top of the canopy or at the ground surface can be expressed as:

$$Q^* = K^* + L^* \tag{1}$$

$$= (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow) \tag{2}$$

$$= K\downarrow(1-\alpha) + (L\downarrow - L\uparrow) \tag{3}$$

where:

Q^* is net (allwave) radiation

$K\downarrow$ is incoming short-wave radiation

α is albedo, the ratio of reflected to incoming solar radiation

L^* is net long-wave radiation

$L\downarrow$ is incoming long-wave radiation

$L\uparrow$ is outgoing long-wave radiation

The computation of this energy budget requires measurements of all energy fluxes above and below the canopy. The instrumentation at the sites did not allow for the collection of all necessary measurements. The net long-wave component of equation (3) had to be calculated. Outgoing long-wave radiation was derived from surface temperatures as follows (Oke 1987):

$$L\uparrow = \varepsilon \sigma T^4 \qquad (4)$$

where:

ε is ground surface emissivity

σ is the Stefan-Boltzman constant ($5.67E^{-8}$ Wm^{-2} $°K^{-4}$)

T is surface temperature (°K)

Since radiation budget calculations began on Julian Day 156, snow was not a factor in modifying surface emissivity. The actual emissivity of the surface was unknown but natural surfaces can generally be assumed to have emissivities close to unity (Eagleston 1970). Because of the varying thickness of the organic layer and slight seasonal movement of sensors due to ground subsidence, $L\uparrow$ calculations for the ROW and burned forest sites were computed from temperatures integrated over the soil surface and the first five centimeters in the burned organic mat. In the control, this value was integrated over the soil surface, lichen mat and tree canopy (Rouse and Kershaw 1971). $L\downarrow$ was calculated as the residual from equation (3).

The solar flux reflected from the top of the black spruce canopy was not directly measured but could be approximated by the expression (Lafleur and Adams 1986):

$$K\uparrow_T = K\downarrow_o (1-\tau)\, \alpha_{TC} + K\downarrow_o (\tau^2)\, \alpha_{GS} \qquad (5)$$

where:

τ is the coefficient of solar transmission through the canopy

α_{GS} is the ground surface albedo

α_{TC} is the tree-crown albedo

In equation (5), τ was calculated as the ratio of incoming solar radiation above canopy and incoming solar radiation below canopy. Because pyranometers were not deployed above canopy, $K\downarrow$ measured on the ROW was assumed to be an adequate surrogate measurement of $K\downarrow$ in the control treatment. The close proximity of the two sites (~1.5-2 km) and the fact that $K\downarrow$ (also $L\downarrow$) is governed by large-scale atmospheric relationships makes this assumption valid (Oke 1987, Lafleur and Adams 1986). The values of α_{TC} were not measured in the field. Values used for calculations were obtained from published literature on the albedo of subarctic surfaces (Petzold and Rencz 1975; Price and Petzold 1984; Wilson and Petzold 1973). Equation (5) is valid insofar as solar transmission through the canopy is assumed to be isotropic (i.e. τ is the same for solar radiation passing upward and downward through the canopy) and multiple reflections of the tree crowns are ignored. The open nature of the canopy with 15% crown closure (Kershaw L. 1988) and the generally small albedo of the tree crowns indicate that the errors associated with the primary assumptions are only a few percent (Lafleur and Adams 1986).

In order to integrate the snow depth and density values and to compare post-fire snowpack modifications, a heat transfer coefficient (HTC) was used. It includes the influence of depth and density in an attempt to assess the potential for heat loss from the various SEEDS treatments (Kershaw 1991). HTC is defined as:

$$\mathrm{HTC} = C/d \tag{6}$$

where:

C is the thermal conductivity of the snowpack

d is the snowpack thickness (cm)

The thermal conductivity of the snowpack was calculated from the formula (Kershaw 1991):

$$C = (2.94E^{-6}\ \mathrm{Wm}^{-1}{}^{\circ}\mathrm{K}^{-1})(\rho)^2 \tag{7}$$

where ρ is snowpack density (kg m^{-3})

Results:

Air temperature and degree index calculations:

During the period preceding the onset of thaw (Julian days 50-115), mean daily air temperature at +150 cm was lower than control in the trench treatment. The burned forest and ROW treatments were 0.12°C. and 1.26°C warmer than the control during the same period (Table 2-1 A). Between Julian Days 116-162, the burned forest and trench treatments were cooler than the control. Differences varied from 0.1°C to 2.26°C. During the same period, temperature on the ROW

A)

Measurement Period (Julian Days)	Burned Forest		ROW		Trench	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
50-115	0.12	0.85	1.26	4.13	-0.35	4.10
116-122	-0.24	1.20	0.46	1.82	-0.91	1.81
123-129	-0.31	0.45	-0.99	3.46	-2.26	3.30
130-136	-0.76	0.22	0.92	2.46	-0.10	2.39
137-142	-0.65	0.19	-0.97	4.13	-1.93	4.05
143-149	-0.40	0.39	0.50	4.49	-0.63	4.37
150-156	-0.78	0.47	-0.01	4.00	-0.83	3.72
156-162	-0.43	0.49	-1.14	6.82	-1.49	6.64
162-204	no data	no data	no data	no data	no data	no data
205-211	1.25	5.30	1.68	5.29	1.20	5.18
212-218	-1.81	1.92	-1.41	1.90	-2.03	1.82
219-225	0.38	3.75	0.78	3.74	0.12	3.69

B)

Measurement Period (Julian Days)	Burned Forest		ROW		Trench	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
50-115	1.43	1.40	1.17	2.09	3.50	2.77
116-122	-1.56	1.21	0.92	1.31	2.58	1.11
123-129	-1.06	0.83	-0.71	2.54	0.55	2.67
130-136	-0.08	0.45	1.47	2.52	1.81	2.45
137-142	2.24	0.68	1.37	4.40	1.19	4.06
143-149	1.24	1.01	1.65	4.03	2.06	3.70
150-156	1.11	2.15	1.18	3.66	1.68	3.78
156-162	0.77	0.91	-0.05	5.94	0.35	6.19
162-204	no data	no data	no data	no data	no data	no data
205-211	2.11	4.79	1.73	4.80	2.32	4.39
212-218	-0.84	1.58	-1.19	3.42	-0.71	1.36
219-225	0.98	3.49	0.79	3.38	1.40	3.28

Table 2-1: Mean air temperature differences and standard deviations between the control and burned treatments at heights of **A)** 150 cm and **B)** 10 cm. Measurement periods include the "winter" period before snowmelt (Julian Days 50-115) and weekly segments for the rest of the measurement period. The data period between Julian Days 162-204 is missing due to sensor malfunction. All temperatures are in °C.

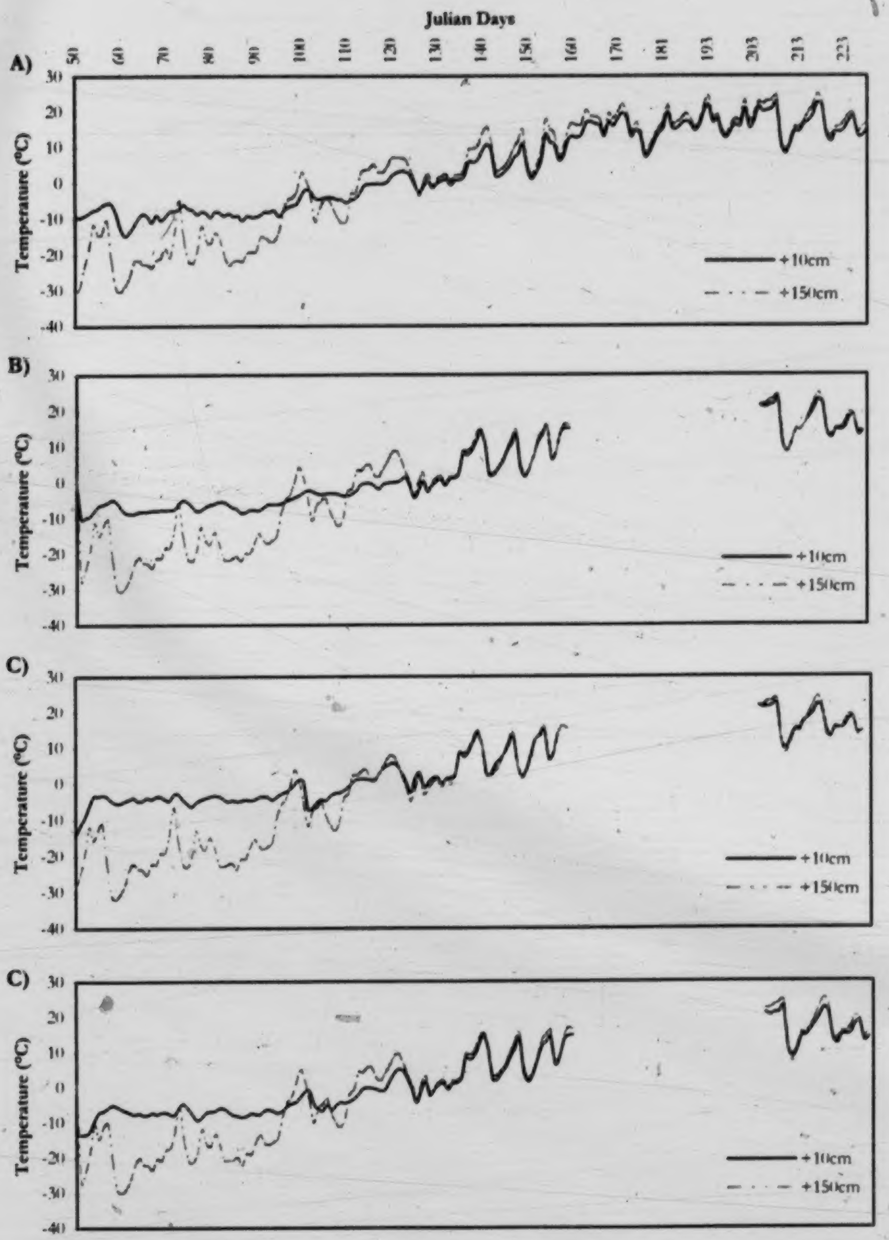

Figure 2-2: 1997 air temperature measurements at standard heights for A) Control treatment, B) Burned Forest treatment, C) Trench treatment and D) ROW treatment.

fluctuated above and below the mean control temperatures. The ROW exceeded the control temperature on three occasions (Table 2-1 A). The maximum difference reached 0.92°C (Julian Days 130-136). The ROW was also cooler than the control on four occasions with a minimum temperature difference of 0.99°C (Julian Days 123-129). During the last 20 measurement days, all burned treatments were warmer than the control, except for the period between Julian Days 212-218.

Mean daily air temperature at +10 cm was much more variable than that measured at +150 cm. During the winter period (presence of significant snowpack on the ground), up to the commencement of thaw, temperatures were coldest on the ROW, followed by the burned forest and trench treatments. When compared to the trench, mean daily temperatures were generally 3-4°C cooler on the ROW and burned forest treatments. Temperatures in the control were similar to the SEEDS values (Figure 2-2).

Mean daily air temperature at 10 cm was more variable than at a height of 150 cm. The burned forest exhibited the most variation as standard deviation values were 40%-50% greater than 150cm values. During the winter period, the trench was the warmest burned treatment followed by the burned forest and ROW. Following thaw and for the remainder of the summer period, the trench remained warmer than the control (with the exception of one week between Julian Days 212-218) (Table 2-1 B) (Figure 2-2).

The highest *Thawing Degree Index* (TDI) was recorded in the burned forest, followed by the control and ROW treatments. The trench had the lowest TDI, constituting a difference of 9% from the burned forest. The *Freezing degree Index* (FDI) was greatest in the trench and decreased in the control , ROW and burned forest treatments respectively. The trench *FDI* was 11% greater than the burned forest. The difference in thawing-freezing degree indexes (Δ) indicated a 52% greater number of freezing degree days for the trench (Table 2-2).

Degree Index	Burned Forest	ROW	Trench	Control
Thawing	773.50	738.14	707.94	761.67
Freezing	-927.63	-965.40	-1029.29	-964.52
Δ	-154.13	-227.26	-321.35	-202.85

Table 2-2: 1997 degree index calculations for the SEEDS and control treatments. The data period used for calculations is from Julian Days 51-161 (FDI) and 204-227 (TDI).

-Relative humidity

The pattern of relative humidity distribution was similar in all four treatment types. The principal difference was the greater amplitude of the relative humidity in the control when compared to the other treatments. Peaks in relative humidity in the control were 23-25% greater than for the SEEDS treatments. Minimum values only differed by 3-5% between burned and unburned treatments (Figure 2-3).

-Wind speed

The control treatment had lower mean daily wind speed than the burned treatments. The average for the whole measuring period indicates wind speeds that were 0.63-0.66 ms^{-1} and 0.68-0.71 ms^{-1} lower at +300 cm and +150 cm respectively in the control stand. Among the burned treatments, wind speeds were slightly higher in the burned forest than on the ROW (0.03 ms^{-1} at +300 cm and +150 cm)(Figure 2-4).

-Radiation budget

Incoming short-wave:

Levels of incoming short-wave radiation were similar on burned forest and ROW surfaces (Figure 2-5 A). The difference was less than 2%. In the control, radiation levels were 50-200 Wm^{-2} lower than the burned treatments. Minimum radiation levels were within 2% at all treatments and the greatest differences occurred during peaks of maximum radiation (Figure 2-5 A).

Outgoing short-wave:

The pattern of outgoing radiation was similar in all treatments. ROW and burned forest exhibited similar levels of outgoing radiation throughout the measurement period (Figure 2-5 B). During peaks, the control treatment exhibited levels that were 20-30 Wm^{-2} lower than the burned treatments. Additionally, during periods of radiation minima, levels were equal at all burned sites. Radiation levels at the burned treatments were 3-5 Wm^{-2} higher than the control (Figure 2-5 B).

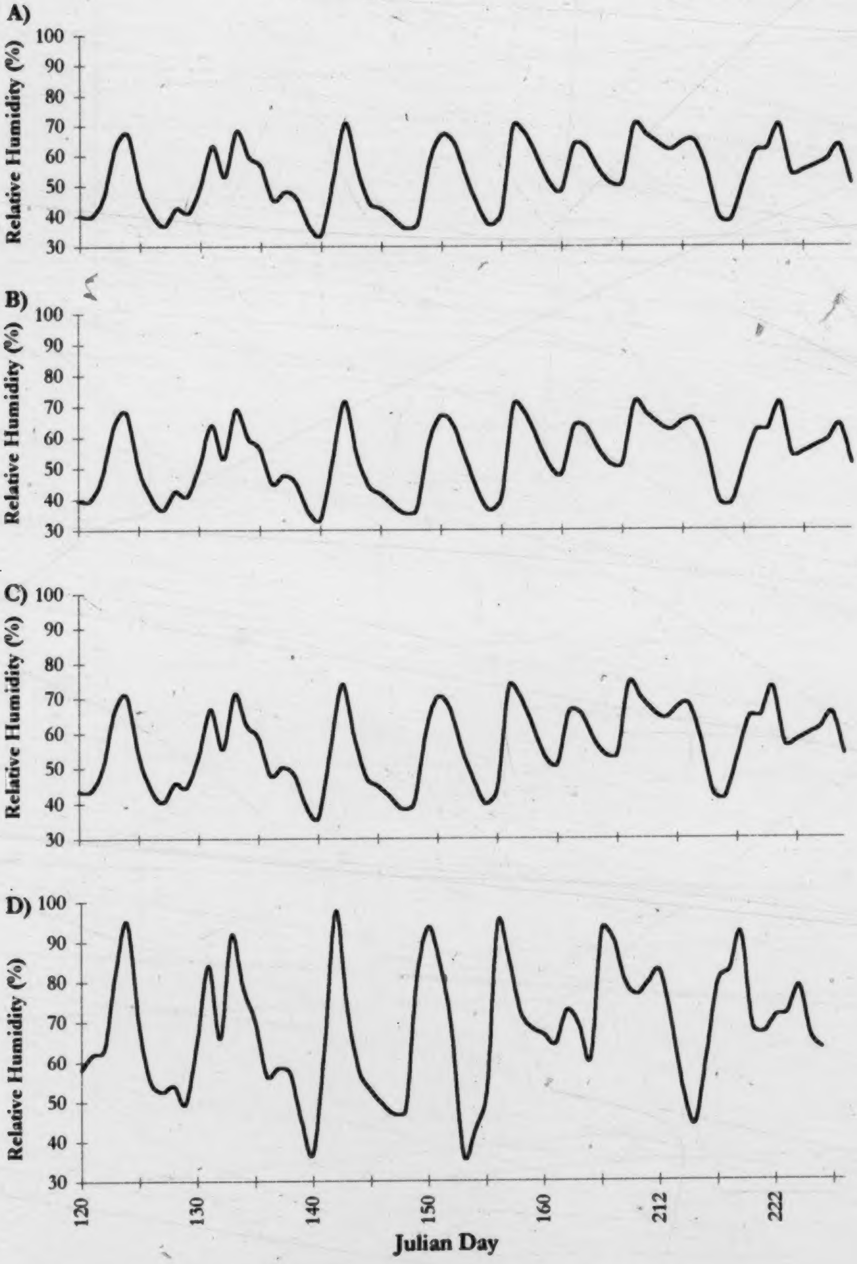

Figure 2-3: 1997 relative humidity measured at 150 cm in A) Burned Forest treatment, B) ROW treatment, C) Trench treatment and D) Control.

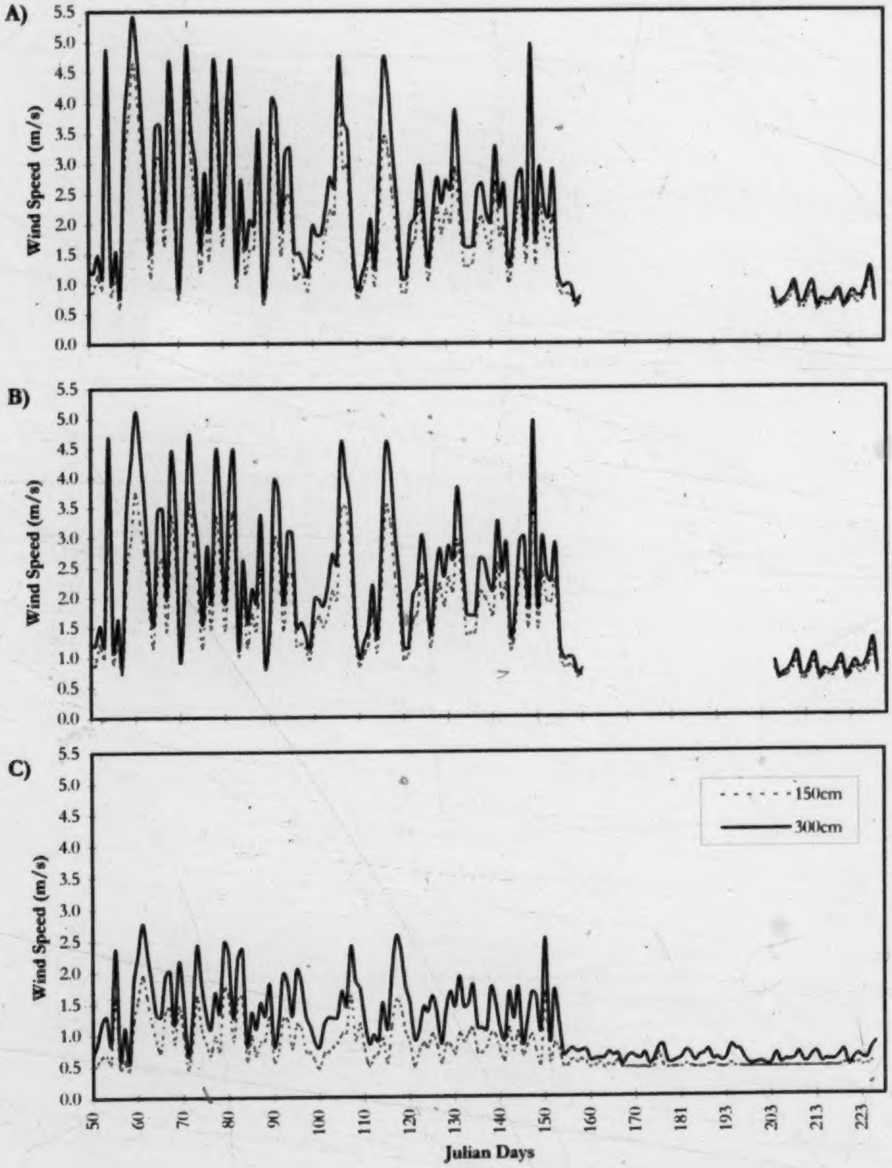

Figure 2-4: 1997 mean daily wind speed measured at two standard heights in A) Row treatment, B) Burned Forest treatment and C) Control treatment. Wind speeds include a programmed offset of 0.447 m/s. Line breaks are due to data gap.

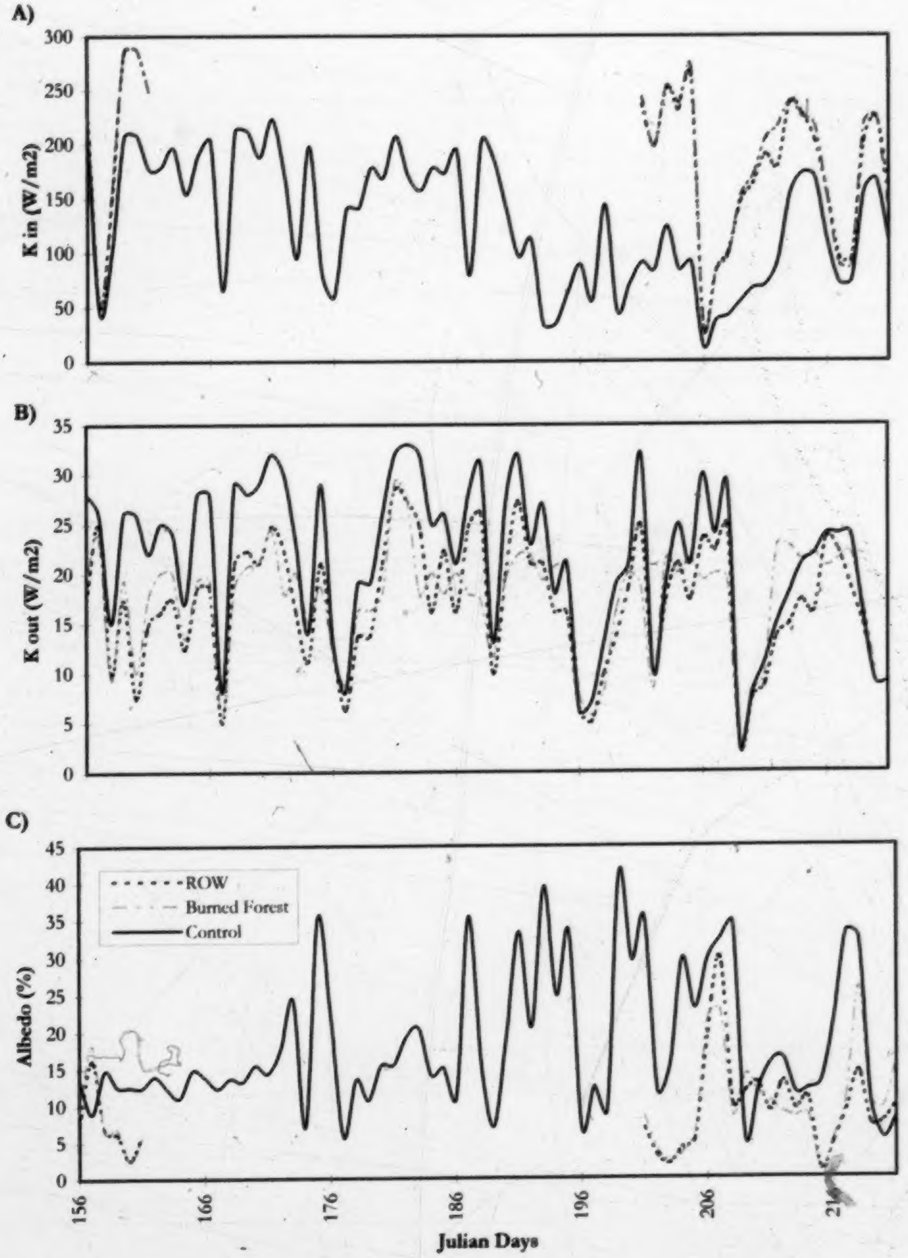

Figure 2-5: 1997 mean daily short-wave energy flux components for the ROW, Burned Forest and Control treatments; A) Incoming short-wave radiation, B) Outgoing short-wave radiation, C) Albedo (calculated). Line breaks are due to data gap.

Albedo:

Albedo was highest in the control treatment. Values fluctuated between 7% and 41%. In the burned treatments, albedo values varied between 2% and 18%. During periods of minima, albedo values were similar in both burned treatments. Peaks in albedo were higher on the ROW for the period between Julian Days 203-208. This situation was reversed between Julian Days 217-219 when the Burned Forest albedo was higher than the ROW (Figure 2-5 C).

Incoming long-wave:

Incoming radiation was highest in the control treatment. During periods of concurrent data, peaks in long-wave radiation in the control were 50-300 W m^{-2} greater than the burned treatments (Figure 2-6 A).

Outgoing long-wave:

Outgoing long-wave radiation was highest in the burned forest although the control had values that were generally within 10 W m^{-2}. In contrast, the ROW values were 35-50 W m^{-2} lower. Peaks and fluctuations were synchronous in the burned forest and control treatments but this was not the case in the ROW treatment. This distribution was more constant with an absolute seasonal amplitude of 50 W m^{-2} in comparison to the ~90 W m^{-2} amplitude in the other two treatments (Figure 2-6 B).

Net allwave radiation:

Net radiation was highest in the two burned treatments where the distributions were identical throughout the measuring period. The pattern of radiation in the control resembled the other two distributions, the principal difference being lower radiation levels in the control. Peaks of net radiation in the burned treatments frequently reached 180-200 W m^{-2} while corresponding peaks in the control attained 140-150 W m^{-2} (Figure 2-6 C).

-Radiation budget comparisons between burned and control treatments:

Short-wave radiation and albedo:

Incoming short-wave radiation in the control treatment was 21-50% lower than in both burned treatments. Outgoing short-wave radiation in the burned treatments was lower than the control by 14-30%. Ground surface albedo was greatest in the control treatment. Values were generally 35-67% lower in the burned treatments (Table 2-3, Figure 2-7).

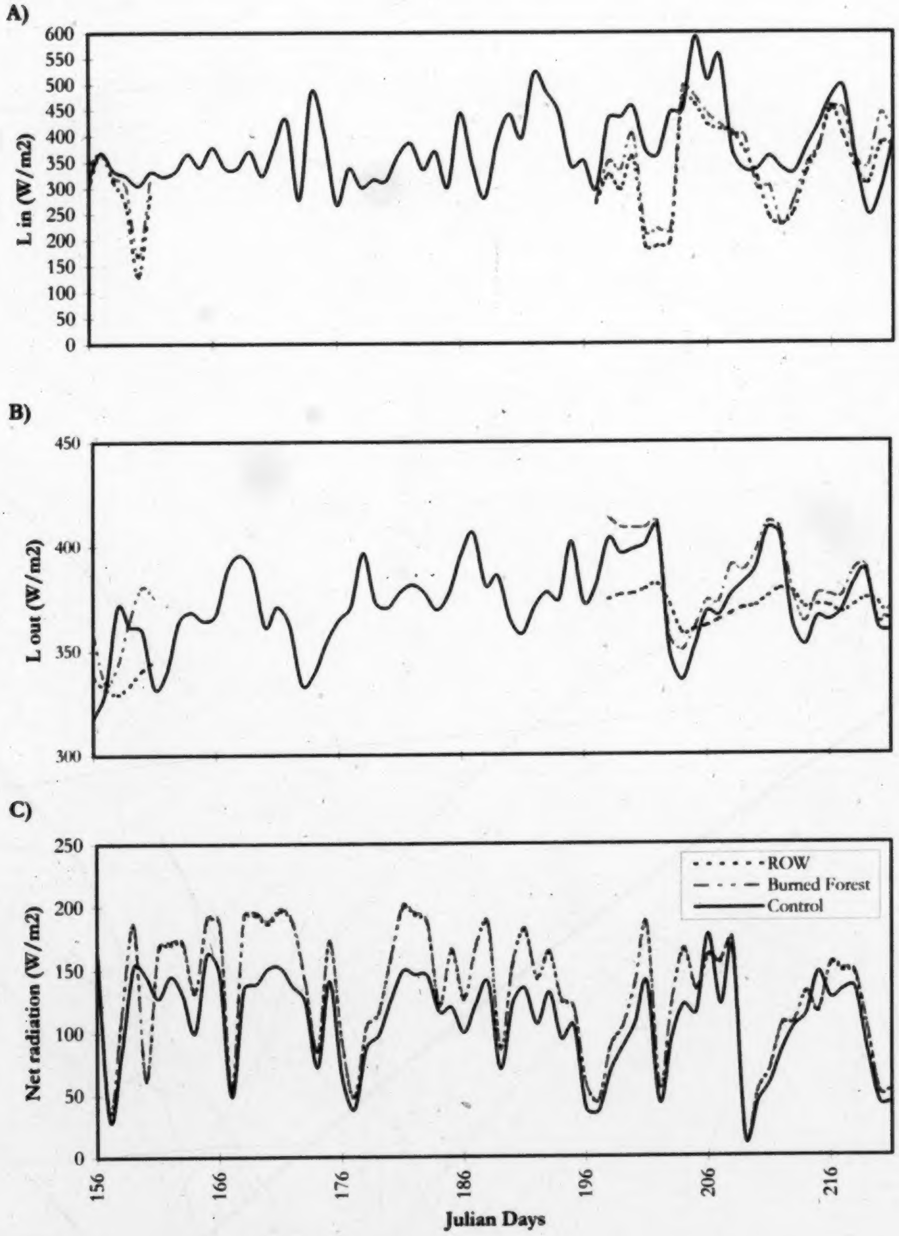

Figure 2-6: 1997 long-wave and net energy flux components for the ROW, Burned Forest and Control treatments; A) Calculated incoming long-wave radiation, B) Modelled outgoing long-wave radiation, C) Net radiation. Line breaks are due to data gap.

Long-wave radiation:

Incoming long-wave radiation was greater in the control than in both burned treatments. Differences varied between 4-33%. Outgoing long-wave radiation was generally greater in the burned forest, closely followed by the control treatment. With the exception of the period between Julian days 210-216, the ROW treatment exhibited the lowest levels of emitted long-wave radiation (Table 2-3, Figure 2-7).

Julian		K in			K out		Tree crown		Albedo	
Days	B. Forest	ROW	Control	B.Forest	ROW	Control	K out	B. Forest	ROW	Control
156-162	208.8	209.0	160.7	16.5	15.6	22.6	23.6	0.079	0.075	0.141
196-202	186.7	186.0	74.9	18.8	18.2	22.0	20.1	0.101	0.098	0.294
203-209	186.1	182.7	93.3	14.1	14.2	17.3	20.5	0.076	0.078	0.185
210-216	161.4	162.3	123.0	15.8	17.0	20.0	21.6	0.098	0.105	0.163
217-221	121.1	128.8	101.8	15.1	14.6	17.8	15.8	0.125	0.113	0.175

Julian		L in			L out			Q*		
Days	B. Forest	ROW	Control	B.Forest	ROW	Control	B. Forest	ROW	Control	
156-162	296.5	270.9	325.8	359.5	336.4	345.6	129.3	127.9	121.6	
196-202	339.1	305.8	397.7	410.4	377.8	401.6	96.7	95.8	74.4	
203-209	338.3	328.0	494.3	377.1	364.7	369.1	133.2	132.1	115.9	
210-216	340.6	333.5	364.5	380.4	374.0	369.9	105.8	104.8	96.9	
217-221	377.8	361.2	371.8	377.9	369.7	371.8	101.8	100.6	89.2	

Table 2-3: Weekly averages of radiation budget components for the Burned Forest, ROW and Control treatments during the 1997 measurement period. All radiation fluxes are in Wm^{-2}.

Net radiation:

The computation of the net radiation budget revealed the highest net radiation levels in both burned treatments. Net radiation was generally 5-23% lower in the control. Among the burned treatments, the burned forest exhibited radiation levels that were 0.8-1.1% higher than the ROW treatment (Table 2-3, Figure 2-7).

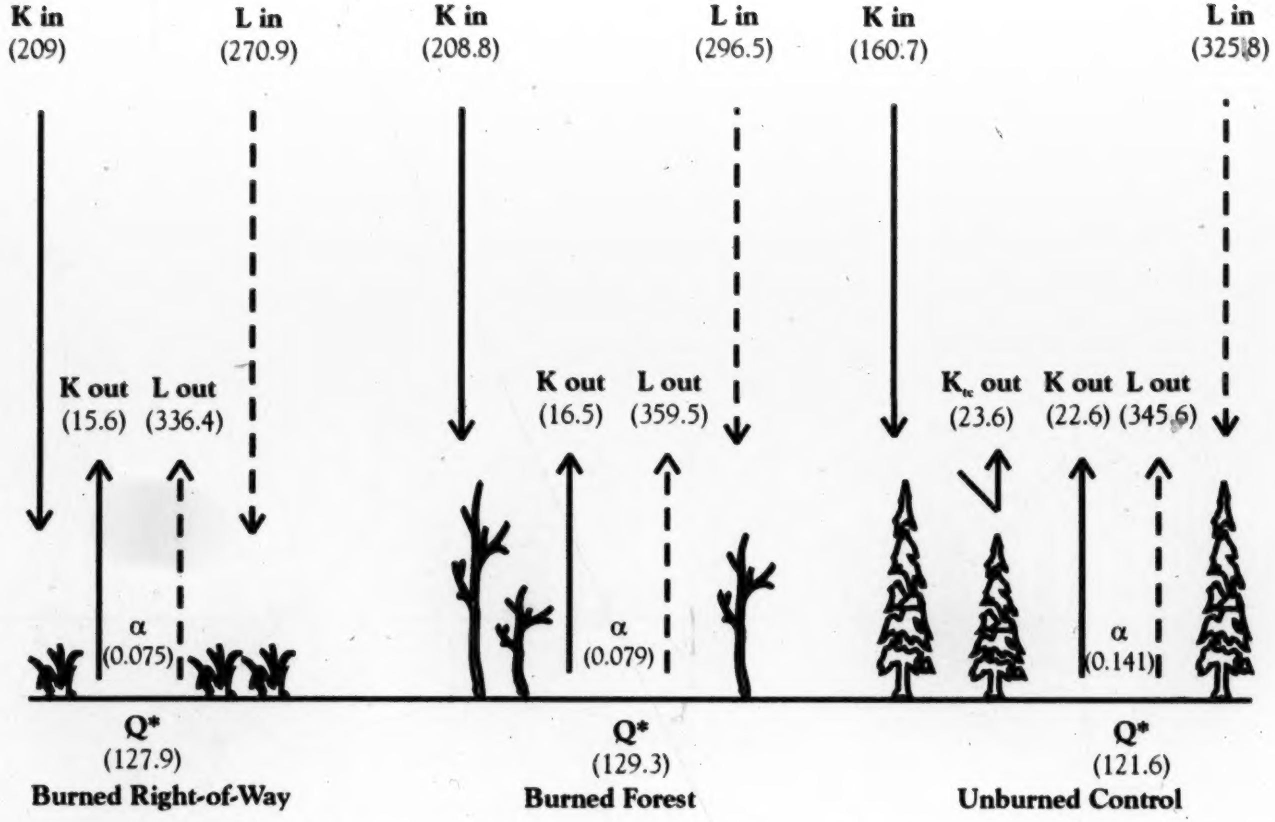

Figure 2-7: Radiation fluxes and energy partitioning over the ROW, Burned Forest and Control treatments for the measurement period between Julian Days 156 and 162 (6 June- 11 June 1997).

-Soil temperatures:

Mean monthly calculations of soil temperatures were obtained from the mean daily temperature data. During "winter" months (January, February, March and April), the trench was the warmest of all treatments with surface temperatures of ~-2°C. Throughout this period, the control treatment remained the coldest with surface temperatures of -6 to -8°C. ROW and Trench sites had similar temperature profiles during the four winter months. The ground surface temperature varied between -6 and -8 °C (January, February, March) and -2°C (April). All temperature curves converged at a depth of ~150 cm where mean temperature was below 0°C (Figure 2-8).

During spring and summer months (May, June, July, August), surface temperatures became positive. The control treatment was one of the coolest treatments at all depths during May and June. This changed in July-August when the trench was the coldest treatment. In May and June, all treatments attained a temperature of 0 °C at a minimum depth of 50 cm (Figure 2-7). In July and August, trench and control temperatures remained below freezing at 90 cm depth whilst burned forest and ROW treatments only reached 0°C at a depth of 150 cm. Surface temperatures gradually increased during the "summer" period, varying from 4-4.5°C (May) to 17-18°C (August) (Figure 2-8).

-Snowpack characteristics:

Snowpack depth:

In February 1997, mean snowpack depth in the control treatment was 54.28 cm (*n*=60, S.D.=3.62). For the same period, mean depth was only 3% (1.57 cm) greater in the burned forest than in the control. Snowpack depth was more variable in the burned forest as standard deviation values were greater by 5.94 cm (Table 2-4 A, Figure 2-9 A).

Along the north-south oriented ROW, snowpacks were deeper on the western edge and slowly thinned towards the eastern edge where depth was 9.51 cm shallower. Variability in snowdepth was also greatest on the west edge as it also decreased with an eastward trend. Along the east-west oriented ROW, snow depth was greatest in the trench, closely followed by the eastern edge. ROW center was 41% shallower than the trench. Snow drifting was noted on site as evidenced by the development of small snow ridges on the leeside of burned standing snags.

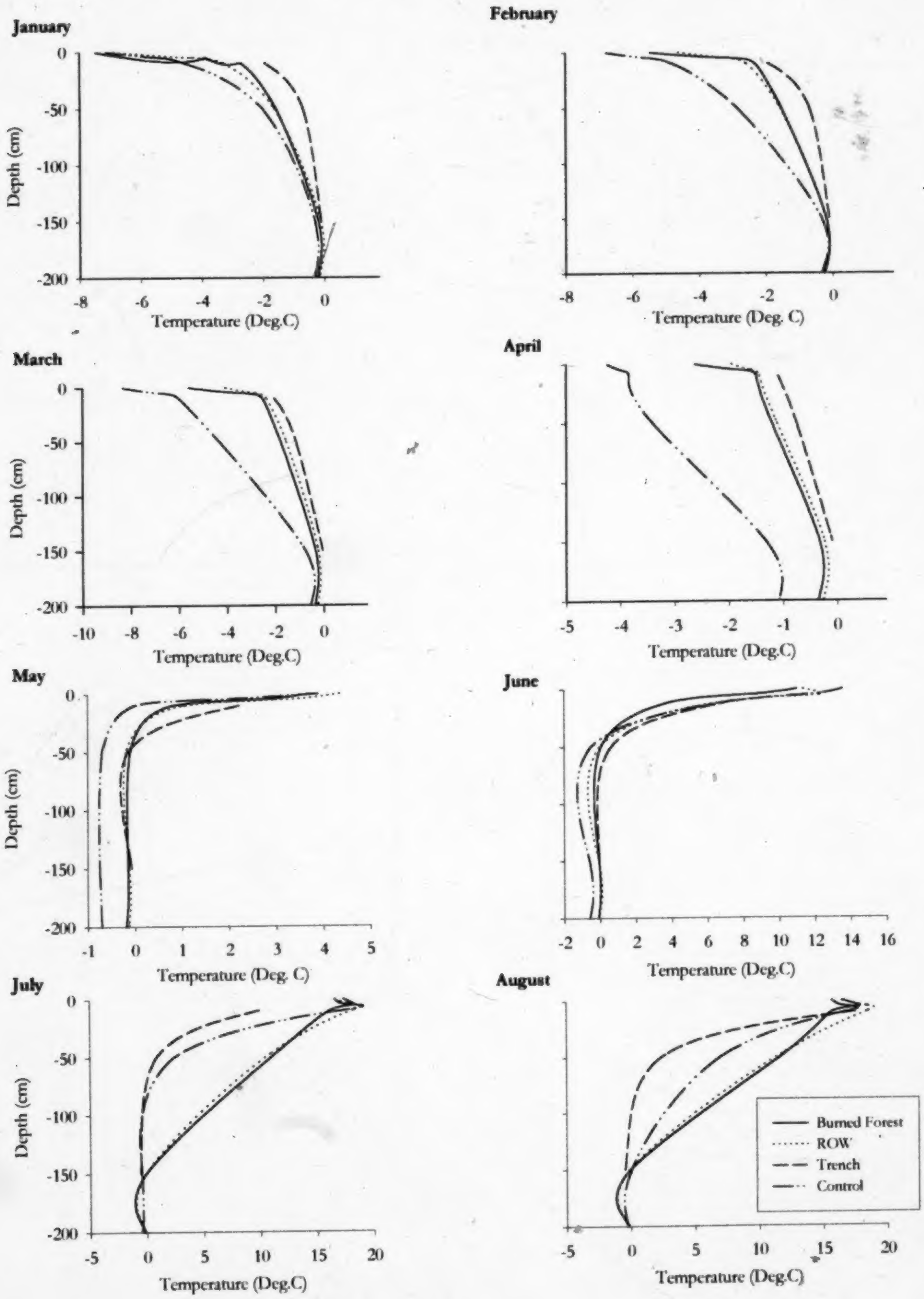

Figure 2-8: 1997 mean monthly soil temperature profiles for the four SEEDS treatments

A)

Control Forest			Burned Forest			Simulated transport corridor with north-south oriented ROW											
			West			West			Center			Trench			East		
Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.
54.28	60	3.62	55.85	40	9.56	50.487	10	22.319	47.00	5	7.50	41.92	25	5.37	40.00	5	2.74

Leading edge of burned forest			Simulated transport corridor with east-west oriented ROW									Leading edge of burned forest		
East			Center			Trench			East			East		
Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.
38.00	10	19.54	29.40	5	1.1402	50.80	15	15.262	49.6	5	5.0299	58	5	3.94

B)

Control Forest			Burned Forest			Simulated transport corridor with north-south oriented ROW											
			West			West			Center			Trench			East		
Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.
154.9	60	6.73	182.19	40	18.419	214.33	10	134.26	158.69	5	17.21	145.73	25	19.304	149.1	5	16.903

Leading edge of burned forest			Simulated transport corridor with east-west oriented ROW									Leading edge of burned forest		
East			Center			Trench			East			East		
Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.	Mean	*n*	S.D.
161	10	31.04	152.9	5	6.8919	166.24	15	21.262	149.19	5	17.3	174.14	5	18.65

Table 2-4: Summary of February 1997 **A)** snowpack depth characteristics and **B)** snowpack density characteristics associated with the SEEDS simulated transport corridor. Snow depth given in cm and snow density given in Kg/m3.

The leading edge sites exhibited the greatest overall snowpack depth of all SEEDS treatments, including the control treatment (Table 2-4 A). Mean snow depth was 3.72 cm greater than control with only a 0.32 cm difference in standard deviation.

Snowpack density:

When compared to the control, snowpack density was greater in all burned forest treatments. Along the ROW, the trench, the eastern edge of the north-south oriented ROW and the center and eastern edge of the east-west oriented ROW densities were lower than in the control.

In the burned forest, the westernmost section exhibited the highest density. This was followed by the eastern leading edge sites. The difference between these sites varied between 8.1 and 29.3 kg m^{-3} (Table 2-3 B, Figure 2-9 A).

Along the north-south oriented ROW, snow density decreased from the western to the eastern edge (214.3 kg m^{-3} to 149.1 kg m^{-3}). Only the western edge and the ROW center had density values greater than the undisturbed forest. The greatest overall snow density was observed at the western edge sites. The trench sites had the lowest snow density of all sites (145.7 kg m^{3}).

The east-west oriented ROW had snowpack densities that were generally lower than the control by 2-5.7 kg m^{-3}. The only exception was the trench with density values 11.3 kg m^{-3} greater than the control (Table 2-3 B, Figure 2-9 A).

Leading edge sites had mean snowpack densities that were 6.1-19.2 kg m^{-3} greater than values from undisturbed treatments.

Differences in snowpack depth and density between burned and control treatments:

Post-fire snowpack depths of disturbed sites were greater than control at only three sites: BFW, BRW, BFEE (Figure 2-10 A). However, these differences were slight, averaging 1.5 - 4 cm. At all other sites, snowpacks were thinner than the control treatment. Both transport corridors exhibited snowpack thinning. The greatest difference was noted in the center portion of the east-west oriented ROW where the snowpack was ~25 cm thinner than the control and ~26.5 cm thinner than the burned forest.

Sites with greater-than-control snowpacks also had greater densities. The differences ranged from ~6-59 kg m^{-3}. Additionally, three sites with lower-than-control snowpacks had greater densities: BRC, BFE, BET. Differences only ranged from 4-12 kg m^{-3} (Figure 2-10 A).

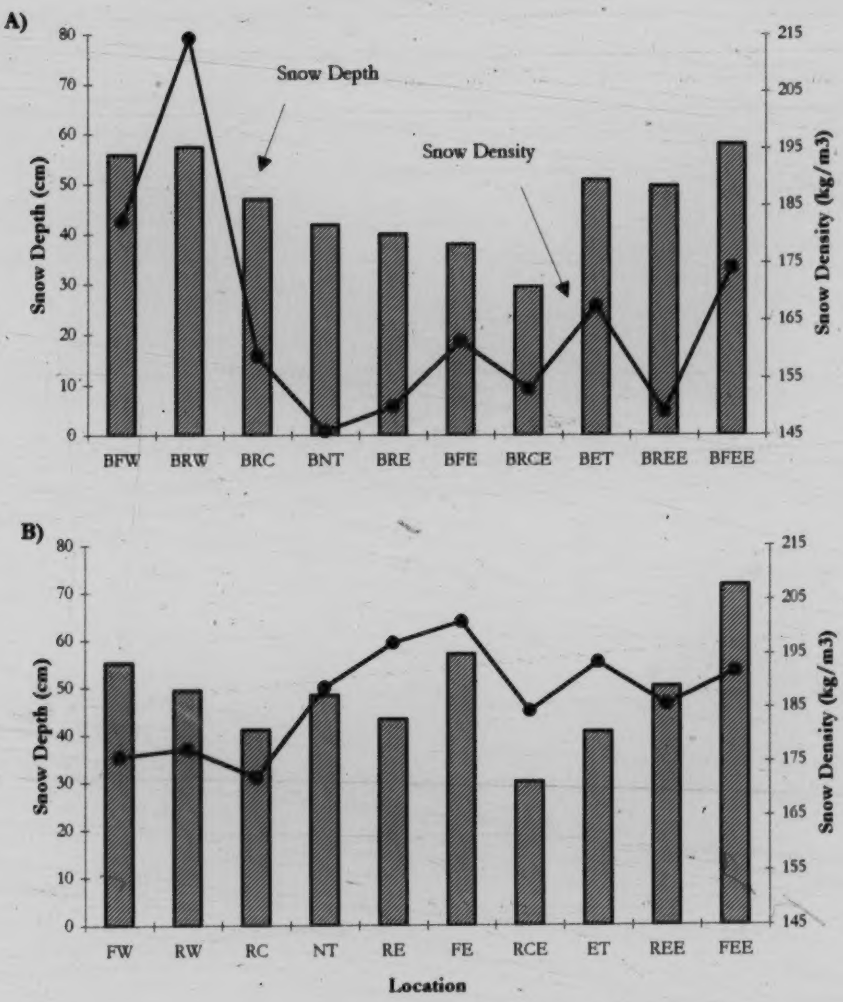

Figure 2-9: Comparison of mean A) post-fire, February 1997 snowpack depth and density and B) pre-fire, February 1986-1989 snowpack depth and density (Kershaw 1991) on a simulated transport corridor. Key to locations: (B)FW - (burned) forest upwind of rights-of-way (ROW); (B)RW - (burned) west edge of north-south-oriented ROW; (B)RC - (burned) center position on north-south-oriented ROW; (B)NT - (burned) north-south-oriented simulated pipeline trench; (B)RE - (burned) east edge of north-south-oriented ROW; (B)FE - - (burned) leading edge of forest on east side of north-south-oriented ROW or south side of east-west-oriented ROW; (B)RCE - (burned) center portion of east-west oriented ROW; (B)ET - (burned) east-west-oriented pipeline trench; (B)REE - (burned) east edge of east-west-oriented ROW; (B)FEE - (burned) leading edge of forest on east side of east-west-oriented ROW.

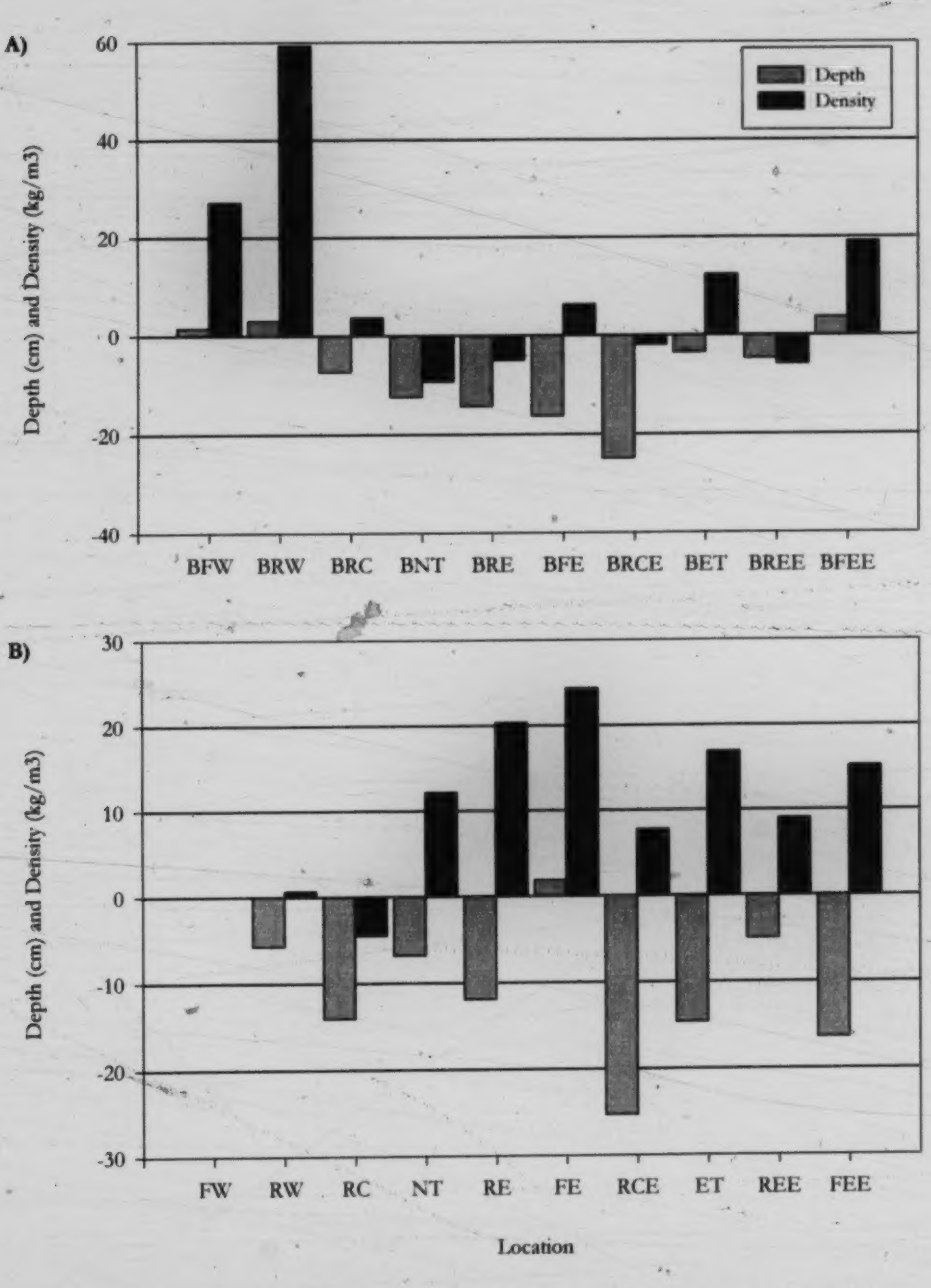

Figure 2-10: Differences in depth and density between snowpacks on, or affected by a simulated transport corridor and an undisturbed forest in **A)** post-fire conditions (February 1997) and **B)** pre-fire conditions (February 1986-1989). See caption Figure 2-9 for explanation of location.

Heat transfer coefficient (HTC):

ROW:

The lowest HTC values were recorded at sites along the transport corridor. All ROW HTC values were below 0.165 W m^{-2} °K^{-1}, the lowest being 0.135 W m^{-2} °K^{-1} at the eastern edge of the east-west oriented ROW. The only exceptions were the centre portion of the east-west oriented ROW and the western edge of the north-south oriented ROW which exhibited the highest HTC values (0.23 W m^{-2} °K^{-1} and 0.24 W m^{-2} °K^{-1} respectively)(Figure 2-11 A).

Burned forest and leading edge sites:

All burned forest sites had HTC values above 0.156 W m^{-2} °K^{-1}. Within the burned forest, the highest HTC was recorded at leading edge sites where values of 0.2 W m^{-2} °K^{-1} were attained. The second leading edge site had the lowest HTC of all burned forest sites (0.156 W m^{-2} °K^{-1}). However, this was higher than all but one of the ROW sites (BRE) where there was a difference of only 0.08 W m^{-2} °K^{-1} (Figure 2-11 A).

Pre- vs. post-fire differences in HTC:

Pre-fire HTC values were greater at all locations save for the leading edge sites on the east side of the east-west oriented ROW (BFEE), the burned forest site (BFW), and the west edge of the north-south oriented ROW (BRW). The greatest differences occurred at the ROW sites where pre-fire HTC was at least 0.06 W m^{-2} °K^{-1} greater. The east-west oriented ROW sites differed the most from pre-fire values. This was particularly striking at the ROW centre site, the trench site and the east edge site where differences reached ~0.18, 0.085 and 0.08 W m^{-2} °K^{-1} respectively (Figure 2-11 A)

Comparison of pre- and post-fire HTC values with control treatment:

Comparing HTC values of disturbed sites with their respective control treatments is the most reliable method to assess the changes in snowpack conditions following fire. This comparison eliminates the effects of seasonality of the snowpack. In post-fire conditions, control-corrected HTC values were greater than pre-fire values at leading edge sites (BFE and BFEE), on the west edge (BRW) and in the centre of the north-south oriented ROW (BRC). The greatest difference occurred at the BRW site where post-fire HTC difference was 600% greater than in pre-fire conditions (Figure 2-11 B). At all other sites, post-fire control-corrected differences were equal to or lower than pre-fire conditions. The greatest differences occurred on the central portions of the east-west oriented ROW (sites BRE, BRCE and BET) (Figure 2-11 B).

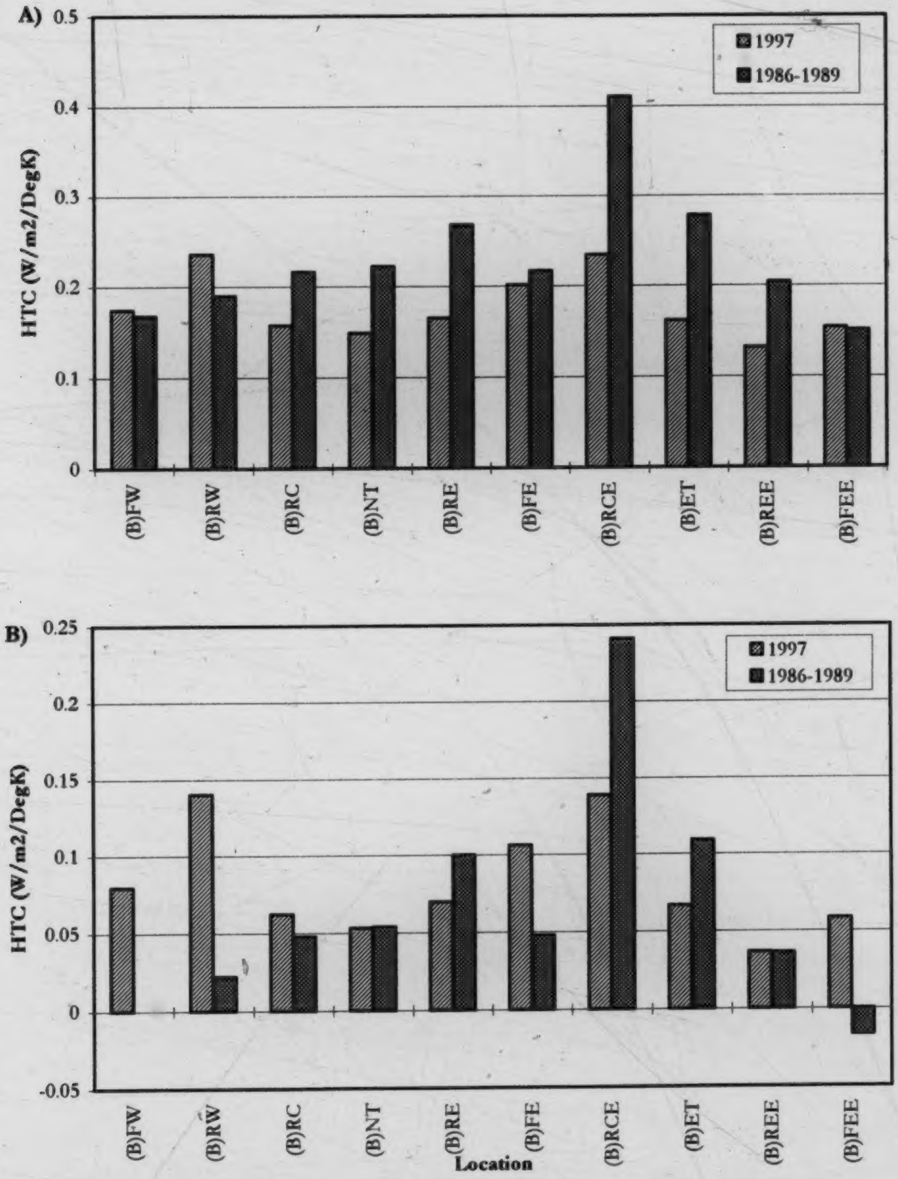

Figure 2-11: A) Comparison of *heat transfer coefficient* (HTC) values between snowpacks on, or affected by, a simulated transport corridor during pre-fire conditions (1986-1989) (Kershaw 1991) and post-fire conditions (1997). **B)** Differences in *HTC* values between snowpacks on, or affected by, a simulated transport corridor and an undisturbed forest during pre-fire conditions (1986-1989) (Kershaw 1991) and post-fire conditions (1997).

Discussion:

Radiation budget comparisons between burned and control treatments

Short-wave radiation and albedo:

The lower levels of incoming short-wave radiation in the control treatment resulted from the presence of trees which partially blocked incoming radiation. The measured radiation levels were lower than results reported by Haag and Bliss (1974 b). They noted that approximately 80% of total incoming radiation penetrated to a height of 2 m, the remainder being scattered or absorbed and re-radiated by taller vegetation. In the control treatment 40-79% of total incoming radiation reached the sensor head at 150 cm height. These lower levels may be due to differences in prevailing weather conditions and the percentage coverage of vegetation at the SEEDS control treatment (47.8%) (Chapter 1) which was 7.8% greater than the coverage reported by Haag and Bliss (1974 a).

Lower levels of outgoing short-wave radiation in the burned treatment were not unexpected considering the abrupt surface darkening after the fire. The albedo values for the burned treatments were consistent with most of the published literature (Rouse and Mills 1976, Kershaw *et al.* 1975, Haag and Bliss 1974 b).

From the weekly averages of the radiation components, it was apparent that short-wave radiation and albedo were the controlling factors on the changes in surface temperatures and, thus, the modification of permafrost. In all treatments, L* (net long-wave radiation) values were always negative as a result of greater fluxes of outgoing long-wave radiation. In comparison, the higher K* (net short-wave radiation) values in the burned treatments led to increases in surface temperatures. Surface blackening and the lowered albedo imparted the greatest control over the partitioning of incoming radiation at the surface. Tree removal also contributed to the dominance of the short-wave radiation component by allowing greater amounts of radiation to reach the surface.

Long-wave radiation:

The burned forest site exhibited the greatest amount of outgoing long-wave radiation. This was not unexpected since fluxes of outgoing long-wave radiation vary only with surface temperatures (Kershaw *et al.* 1975, Oke 1987). At this site, the post-fire albedo decreased, causing greater absorption of solar energy, high surface temperatures and hence high emission of long-wave radiation (Rouse and Mills 1976). It was surprising that the ROW treatment had the lowest levels of outgoing long-wave radiation despite receiving levels of incoming short-wave radiation that were similar to the burned forest treatment. These results may reflect the position of the meteorological station and the topographic characteristics of the ROW itself. Throughout the SEEDS site, the

ROW generally constitutes a depression where rain and meltwater tended to drain. The trench, ROW and adjacent areas were often waterlogged. This high moisture content may have reduced surface temperatures, and hence outgoing long-wave radiation, through increased rates of evaporative cooling of the surface (Oke 1987). This was supported by a trend of increasing long-wave emission during the later part of the measuring period as the surface dried and emissivity may have increased (Figure 2-6 C, Table 2-1). More likely, higher wind speeds on the ROW would dissipate sensible heat more efficiently through greater rates of advection (Haag and Bliss 1974 a).

Higher levels of incoming long-wave radiation were recorded in the control as a result of the tree canopy re-radiating absorbed energy (Haag and Bliss 1974 a, Lafleur and Adams 1986). Additionally, the relatively high levels of outgoing long-wave radiation may have resulted from higher air and surface temperatures as a result of reduced advection (Haag and Bliss 1974 a) and increased trapping of energy by the tree canopy. The high absorptivity of evergreen trees makes them extremely important in the radiation budget of high latitude landscapes (Oke 1987, Lafleur and Adams 1986). Their importance is accented at low solar altitudes as the trees present their maximum surface area for irradiation, and their receiving surfaces are almost normal to the solar beam. Their relative warmth makes them sources of long-wave radiation which is readily absorbed by surrounding surfaces (Oke 1987).

Net radiation:

Net radiation was appreciably greater in both burned treatments than in the control. This was in agreement with Haag and Bliss (1974 a, b) who attributed this increase to the rapid change in surface albedo and a rise in short-wave absorption over the burned surfaces. Additionally, the transpiring plant canopy in the control was able to draw sub-surface moisture through its roots and continue to dissipate a large portion of net radiation as latent heat (Haag and Bliss 1974). However, these findings are contradicted by Kershaw *et al.* (1975) and Rouse and Mills (1976). Kershaw *et al.* (1975) reported a reduction in summertime net radiation lasting up to 81 years.

Most soil temperatures when the soil is frozen, prior to snowmelt, do not differ significantly among the different surfaces, so that the high air temperatures which are achieved in early summer in the burned treatments must be accompanied by a large increase in soil temperatures (G). Additionally, the rates of evaporation decreased substantially after the first year of burning due to lower soil moisture largely resulting from the early melting of the snowcover over the burned surfaces, and the lack of transpiring vegetation, which could have tapped moisture from the deeper soil layers. Because the decrease in evaporation which accompanies burning is greater than the decrease in net radiation, the sensible heat flux over burned surfaces is greater than over unburned surfaces.

In the case of the SEEDS fire this situation may not be directly applicable as a result of the difference in the intensity of the fire. Haag and Bliss (1974 b) have suggested several factors which may explain a decrease in post-fire evapotranspiration despite higher values of net radiation. These included increased resistance due to surface drying, a mulching effect from ash and litter and the removal of the transpiring plants. Although evapotranspiration was not measured at the SEEDS site, it is possible that these three factors accounted for the higher levels of net radiation over the burned surfaces. Also, depending on the intensity of the fire affecting the site studied by Kershaw *et al.* (1975), the litter could have been completely consumed, eliminating the mulching effect of the ash/litter mix and increasing soil surface temperatures. Finally, the lowered evaporation rates one year after burning will depend largely on the moisture and ice content of the active-layer. Surface drying will occur at different rates as a function of surface moisture and evaporation will be prolonged over wetter surfaces. It is possible that the high moisture content of the SEEDS active layer allows evaporation to occur well beyond the first post-fire year.

-Snowpack depth

Control treatment:

During pre-fire conditions, the sections of undisturbed forest between each ROW were used to compare snowpack depths with values from the transport corridors (Kershaw 1991). In 1997, this area was not used as a control treatment as it had burned and the surface conditions were fundamentally altered. The post-fire control treatment where microclimate stations were erected was also used as a control treatment during snow sampling. The lack of data concerning total seasonal snow accumulation at the SEEDS site in both pre- and post-fire conditions restricts direct comparisons of snowpack characteristics. Additionally, using snow on the ground data from the Norman Wells meteorological station as a common control to each site was not possible since the location of the station grossly underestimates snowpack depth (Kershaw 1991).

Burned Forest:

The greater-than-control snowpack depths and densities in the burned forest resulted from the redistribution of snow from unchecked winds. Increased snow density in wind-scoured sites has been reported by Rouse (1982). The removal of vegetation by fire decreased surface roughness in the burned forest, facilitating snow drifting and increasing snowpack density.

North-south oriented ROW:

Along the north-south oriented ROW, the decrease in snowpack depth eastward was a direct consequence of increased erosion of snow on the simulated transport corridor. Although the removal of vegetation in the burned forest substantially decreased surface roughness, the standing snags still affect the boundary layer to a greater degree than on the simulated transport corridor. This effect was enhanced in the winter as most topographic irregularities were infilled by snow and erect shrubs were incorporated in the snowpack (Kershaw 1991). Vegetation removal has increased the distance of fetch for prevailing winds, thereby increasing the degree of snow deflation away from the edge of the ROW. For example, the western edge of the north-south oriented ROW had a mean snowpack depth 5.36 cm less than the adjacent burned forest. This difference increased to 15.85 cm on the eastern edge as fetch along the ROW was greatest at this point. This effect was particularly pronounced at these sites as sampling locations were oriented approximately parallel to the prevailing wind direction.

East-west oriented ROW:

Kershaw (1991) reported that snow drifts accumulated on the leading edge of the forest on the downwind side of the ROWs. This resulted from deflation of the snowpack on the treeless ROWs. Leading edge snowpacks were consequently enhanced by 29.9% and 3.4% over the control on the east-west oriented ROW and north-south oriented ROWs respectively. This contrasted strongly with the post-fire leading edge snow characteristics. The leading edge of the north-south oriented ROW had snowpack depths that were 30% less than the control treatment. Concurrently, the east-west oriented ROW exhibited only a 6% increase over the control. Again, this increase likely resulted from the removal of vegetation between the ROWs and the extended fetch distance. During pre-fire conditions, the tree canopy and low-lying branches slowed wind from the ROWs and forced the deposition of transported snow. In post-fire conditions, tree removal would permit faster wind speeds and increased snow entrainment on the ROWs and downwind ROW edges. This clearly suggests that the removal of vegetation and the associated fetch increase has transformed the forest edges from areas of snow deposition to areas of net erosion.

Snowpack density:

Control treatment

Mid-winter snowpack density in the control treatment was low, but typical of snowpacks in the Subarctic (McKay and Findlay 1971, Pruitt 1984). Additionally, density values were not markedly different than during pre-fire conditions (see Kershaw 1991). These similarities resulted from the open-canopied tree cover that provided surface roughness and reduced snow movement and drifting (Jeffrey 1970, Kind 1981). These conditions permitted *Qali* (Pruitt 1958) build-up and snowpacks that were not overly densified by wind.

Transport corridor

With the exception of two sites (BRW and BRC) on the north-south-oriented ROW density was lower than that observed in the control during post-fire conditions. This was a remarkable change from pre-fire conditions where all sites, *except* RW and RC, exhibited greater snow density than the control (Kershaw 1991). The greatest change occurred on the western edge of the north-south-oriented ROW, where density increased almost 60 fold. This change was again attributed to the increased wind effects on the snowpack. The open nature of the ROWs favored higher wind velocities at the ground level, resulting in increased rates of snow removal. Additionally, the ROWs were areas of snow deposition during periods of decreasing wind velocities. This snow was already mechanically metamorphosed (obliteration of crystal arms through saltation, etc.) and packed with greater density than freshly-fallen snow. This resulted in snowpacks exhibiting decreasing depths and densities across the north-south-oriented ROW. This situation was reversed along the east-west-oriented ROW, where snow depth and density increase eastward. Two sites along this ROW (BRCE and BREE) had density values that were lower than control while two other sites had depth and density values greater than the control. The lower post-fire density values can again be attributed to high rates of snow erosion and metamorphism. Both sites had snow density values similar to the control values (Table 2-1) yet snow depths were 8% and 45% shallower than control. This was a prime example of the densification process associated with snow drifting. It was particularly well exemplified by site BRCE (site 5, Figure 2-1) located on the northern edge of the ROW, had maximized fetch distance for the winds affecting it. For sites BET and BFEE, the high snowpack density values resulted from the length of the ROW and its low surface roughness. In the case of site BFEE, ROW length was again a significant factor in determining the density of the leading edge snowpack since it was the distance over which the snow could be entrained and wind-eroded upwind of the sampling site. Preferential redeposition occurred in the first 3-4 m of the forest as tree snags created enough surface roughness to perturb wind flow and allow deposition. The redeposited drift snow had a higher density due to the modification of grain sizes during transport as well as wind-packing effects (McKay and Gray 1981).

Heat Transfer Coefficient and soil temperatures:

Along the transport corridor, the high HTC values resulted from high snow density. Despite having considerable snow depths. Compared with other sites, these areas would be poorly insulated, resulting in greater winter heat loss than adjacent areas. This should also result in colder near-surface soil temperatures and perhaps enhance frost penetration. Near-surface soil temperatures were indeed colder in the burned forest and ROW treatments. The low HTC values along the trench were suggestive of lower rates of heat loss occurring at these sites. This is in agreement with the soil temperature data with the trench 4-6°C warmer that the ROW and burned forest treatments.

Pre- vs. post-fire comparisons of HTC values:

1997 sites with the greatest HTC differences from the control also had the lowest difference from the 1986-1989 data. This was similar to density in post-fire conditions where there was a reversal of pre-fire conditions. From equations (6) and (7) and the relative importance of snow density (ρ), this influence was expected on the HTC values.

Conclusion:

In the third summer after a wildfire and preceding the onset of thaw, air temperatures were lower in the burned treatments than in the control. This situation was however reversed after the commencement of thaw as the burned ROW and the burned forest were ~2°C warmer than the burned trench and the control treatment.

As a result of the removal of the transpiring vegetation, relative humidity was lower over the three burned treatments. Tree removal reduced surface roughness and affected wind speeds by permitting greater wind velocities in the burned treatments.

Following fire, the radiation budget of the burned surface was fundamentally altered. Burning created decreased albedo from burned surfaces which resulted in an increase in net radiation. Consequently, soil temperatures were warmer in the burned forest and burned ROW treatments. This prompted the movement of the 0°C isotherm 60 cm deeper than in the control treatment.

Burning also altered snowpack characteristics. Snowpacks were generally thinner and denser than during pre-fire conditions. This was a direct result of the removal of vegetation which favored snow redistribution and erosion by wind. Both transport corridors exhibited signs of snowpack thinning as a result of the increased fetch distances. The most significant post-fire modification of the snowpack was a reduction in the variability of snowpack characteristics between the transport corridors and the adjacent burned forest areas.

HTC (Heat Transfer Coefficient) values were lowest along the transport corridor. Two exceptions were however noted: the center portion of the east-west oriented ROW and the western edge of the north-south oriented ROW had the highest HTC values. Within the burned forest sites, the highest HTC values were recorded at leading edge sites. The highest HTC values of the burned forest were greater than all but one of the ROW sites. This suggests that sites in the burned forest and on some areas of the ROWs would be poorly insulated and be subject to colder soil temperatures. This would allow frost penetration to greater depths. The active layer and the top of the permafrost would cool to a greater degree than other treatments. This could temporarily offset the summertime warming that results from increased net radiation over the burned treatments.

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Chapter 3: Soil properties and thaw depth following wildfire in a Subarctic upland forest and on a simulated transport corridor

Introduction:

In Canada, permafrost is present in various forms over almost 50% of the country (Hegginbottom 1995) and its presence creates unique engineering problems. It was quickly recognized that the main concern facing northern development was the degradation of thaw-susceptible, ice-rich permafrost which can cause increases in active layer depths, thermokarst subsidence and mass movement (Brown 1970, French 1976).

Wildfires are one of the most important disturbance affecting permafrost and vegetation in the subarctic region (Viereck 1973 a). A number of studies have been conducted on permafrost conditions following wildfire (Hall *et al.* 1978, Hegginbottom 1971, 1973, Mackay 1977, 1995, Viereck 1973a,b, Viereck and Schandelmeier 1980) and although results have been variable, it is generally agreed that active layers are thicker in the successional stands after fire than in the adjacent, unburned areas (Mackay 1970, 1995, Viereck 1973a, 1982).

Brown (1963, 1983) stated that the heat produced by the fire generally has little immediate effect on the thickness of the active layer since the organic layer seldom burns to permafrost depths. Following fire, it is the change in surface albedo and the removal of vegetation that promotes warmer soil temperatures and deeper thawing.

Published results of permafrost-wildfire studies have been mainly conducted in Alaska (Hall *et al.* 1978, Viereck 1973a, b, 1982, Viereck and Schandelmeier 1980, Wein 1971) and in the continuous permafrost zone of Canada (Hegginbottom 1971, 1973, Mackay 1970, 1977, 1995, Wein and Bliss 1973). There are no reported results concerning the effects of wildfires in the discontinuous permafrost zone of Canada. This paper will address some of this lack of information by presenting some results of the short-term effects of wildfire on the active layer thickness of a simulated transport corridor and adjacent burned forest.

Objectives:

The objectives of this study were:

i) Compare the active layer depths and the soil moisture contents for the various SEEDS treatments following burning.

ii) Compare the post-fire thaw depths and moisture content changes for the SEEDS treatments.

iii) Quantify the active layer changes of a burned black spruce forest in discontinuous permafrost.

Post-fire modifications of the active layer:

In eastern Alaska, at the end of the first summer of an August fire, Lotspeich *et al.* (1970) found no significant differences in active layer depths. Both burned and unburned sites had thawed to depths of ~70cm. Wein (1971) reported an increase of 130-150% in the depth of the active layer in early summer after a fire the previous year. However, this difference had declined to 115-120% by the time maximum thaw was reached in the fall. Brown *et al.* (1969), reported increases of 140-160% 4 years after a fire in a black spruce forest. Additionally, they found increases of 141-152% in thaw depth in a 1-year-old burned area in central Alaska. For the Wickersham Dome fire of 1971, Viereck (1973 b) reported no significant differences in thaw depth between burned and unburned stands during the fall of the first summer after fire. However, during the following thaw season, thawing progressed deeper in the burned than in the unburned stand. Although snowmelt occurred 2 weeks earlier in the burned stand, thawing was similar in both sites until 7 June. Beyond this date, thawing progressed more rapidly in the burned area. A maximum thaw depth of 63cm was attained in the burned stand by 23 August. Maximum thaw in the unburned stand was attained on 6 September and only reached 40cm. Thus, thawing in the burned stand was 157% greater than in the unburned (Viereck and Dyrness 1979).

Regarding the 1968 wildfire at Inuvik, NWT, Hegginbottom (1971) reported no significant deepening of the active layer after the first summer. However, by 1970, thaw depths in the burned areas were 9 cm deeper than in the unburned. Mackay (1970) mentioned much greater increases in thaw depth for the same period. By the end of the first summer after fire, the average increase of thaw was 24.1 cm, representing a 149% thickening. Thaw depths had increased to 34.8 cm (171%) by the end of the second summer. In a follow-up study, Mackay (1995) re-examined the original sites from 1970 and found that some sites had been experiencing active layer increases until 1988. He also noted that there had been aggradation of permafrost during recent years, perhaps as a result of the shading effect of the vegetation. More importantly, Mackay showed that individual site characteristics played an important role in the development of the active layer. Some burned hummock sites, had active layer increases between 9-20 cm during the 1968-1993 period. This was less increase than in some of the unburned sites. It is important to note that thaw depth was not monitored each year and so it is possible that the maximum post-fire thaw depth was not recorded. Permafrost may be aggrading at the site and the values reported my Mackay (1995) may therefore be shallower than the maximum thaw depth.

Post-fire modifications of soil moisture contents:

Few studies have been able to quantify and draw definite conclusions on the soil moisture modifications induced by wildfire. A number of variables affect soil moisture content and therefore make it difficult to quantify annual and seasonal variations. In non-fire conditions, soil moisture content depends on rates and volumes of solid/liquid precipitation, rates of snowmelt, soil texture, etc. Additionally, the presence or absence of vegetation, its type and density will also affect soil moisture through various rates of evapotranspiration. If the effects of wildfires are added to this already extensive list of variables, the spatial and temporal distribution of soil moisture dramatically increases in complexity and, therefore, renders seasonal comparisons of soil moisture contents equally complex. Comparing moisture contents quickly becomes an exercise of gross estimation rather than precise recording. Nonetheless, some general conclusions have been drawn from previous studies.

The effect of fire on soil moisture content seems to depend on the severity of the fire, the type of soil and the nature of permafrost present (Viereck and Schandelmeier 1980). A number of studies have reported increases in soil moisture a short time after burning. (Kane *et al.* 1975, Kryuchkov 1968, Swanson 1996). It is generally agreed that these increases are due to permafrost melting as a result of the rupture of thermal equilibrium. Kryuchkov (1968) argued that, in Siberia, the increased moisture favored rapid plant growth that ultimately caused shallower active layers. Kane *et al.* (1975) and Kershaw and Rouse (1971) suggested the increases in free surface water were a result of reduced evapotranspiration that followed removal of the vegetation. However, on sites with little organic material remaining after fire, moisture contents may be lower. In lichen-woodland sites, Kershaw and Rouse (1971) found that moisture contents were lower and fluctuated more than in unburned sites. They attributed this difference to increased rates of evaporation from the exposed mineral soil in comparison to lichen layers that tend to retain moisture and reduce flux from the soil. Studies comparing decade-old surface disturbances found general trends of soil moisture decrease when compared to undisturbed areas. The degree of change between these sites was highly variable and depended largely on individual site characteristics (Lawson 1986).

More recently, Swanson (1996) presented data suggesting that post-fire moisture contents do not change predictably and that one of the major controls on moisture content was microsite characteristics. He observed that soils with permafrost on the coldest and wettest landscapes (concave to plane, lower slope positions and north-facing midslopes) usually failed to thaw deeply, with no substantial changes in moisture conditions. Soils with permafrost on convexities, crests and shoulders and east-,west- or south-facing midslopes thawed deeply in some instances and not in others, presumably as a function of fire severity or frequency.

Field methods:

Frost probing:

In 1986, four parallel frost probe transects were established at the SEEDS site. These transects crossed the site from west to east and were used to monitor the progressive increase in active layer thickness during the thaw season (Gallinger and Kershaw 1988). This setup was used from 1986 until the 1995 wildfire and several surveys were conducted annually. In 1996, a new network of probe sites was implemented, this time with two transects. Additionally, a second network of probe sites was set-up in an unburned stand of *Picea mariana* located ~3 km north of the SEEDS site. This area has been used as a control since the beginning of the 1996 thaw season. Active layer depth measurements were collected using a solid, 2-m-long and 1-cm-wide stainless steel rod graduated in 1 cm increments. A similar 3-m-long probe was also used in areas where active layer depths exceeded the probing capability of the shorter probe. The technique used is described by Mackay (1977), where the position of the 0° C isotherm is inferred by probe refusal, indicating that frozen ground has been reached. Mackay (1977) discussed the potential errors associated with this method. Namely that probe rejection can occur well above or below the 0° C isotherm depending on soil texture. To address this potential error source, a third type of probe was used in 1997. It consisted of a hollow, 2 m-long and 1 cm-wide stainless steel rod where two type-T, 44-guage thermocouples were inserted. The thermocouples were connected to a dual display digital thermometer (model Omega HH202) (Figure 3-1). Because of the long thermocouple calibration times required, this probe was used at every fifth probe point along each transect. This permitted the verification of temperatures when rejection depths were reached. A margin of 0.1°C was deemed a sufficient indicator of maximum thaw depth. This margin was also considered to be within the range at which the zero-curtain/frozen fringe effect can occur (Rouse 1976, Hinkel and Nicholas 1995, Williams and Smith 1989). Between 1986 and 1993, the number of probe sites varied from 339 (1986) to 364 (1993) due mainly to the extension of the transect lengths. In 1996 and 1997, 57 probe sites were used along each of two transects on the SEEDS site. Additionally, 50 sites were probed in the control treatment. Probe site spacing varied from 10 m on the ROW's and in the burned forest to 0.5 m across the trenches. Due to time and logistical constraints, the thaw depth was usually not monitored beyond the third week of August. This prevented recording of the maximum thaw depth. Nonetheless, it has been shown that 90% of active layer thickness is attained by late August and that a very small increase usually follows (Viereck 1982).

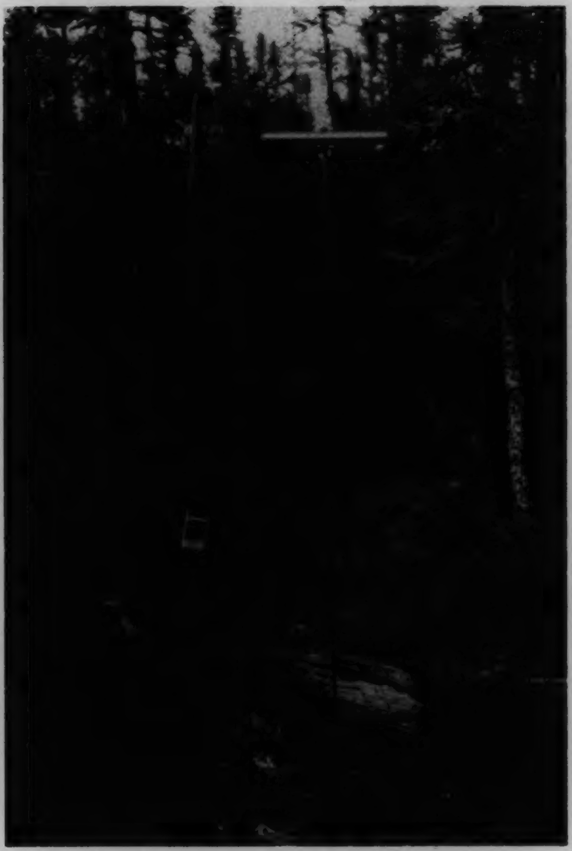

Figure 3-1: Permafrost probe (right) and permafrost/temperature probe (left) used to measure thaw depth in 1997.

Soil coring:

Soil moisture contents and particle size/texture were determined from soil cores extracted from the various SEEDS treatments. Coring was performed over a four day period in May and August 1997. A total of 32 cores were extracted during these periods. In each treatment, sample sites were randomly selected. A total of 8 cores were extracted from the trench, 4 from each ROW, 8 from the burned forest and 4 from the control treatment. The sampling was performed with a hand-driven corer similar to that described by Zoltai (1978). An effort was made to extract core segments of 10-15 cm. This was not always possible and core segment length varied from 7 to 21 cm. Following extraction, samples were promptly bagged and kept cool. During the August coring period, samples were weighed a few hours after extraction.

Laboratory methods:

Moisture content and texture analysis:

Moisture content was determined by weighing samples in the field and again after being oven-dried at 105 ± 5° C (Kalra and Maynard 1991). Moisture content was expressed on a wet weight basis (total moisture) thereby avoiding awkward moisture contents of more than 100% (Tsytovitch 1975). Total moisture was calculated using the following formula:

$$\text{Moisture content} = \frac{\text{Moist wt (g)} - \text{Oven dry wt (g)}}{\text{Moist wt (g)}} * 100$$

Texture analysis was performed using the Boyocous hydrometer method as outlined in Kalra and Maynard (1991).

Statistical analysis:

Due to the small sample sizes obtained during coring, statistical analysis of moisture contents was not possible. However, the thaw depth sampling was sufficient and statistical analysis was performed. The data were compiled using the Microsoft Excel spreadsheet program and statistical analysis was performed using the SigmaStat analysis package. A combination of the Excel and SigmaPlot programs were used to graph the data.

The data were first tested for normality using the Kolmogorov-Smirnoff test for goodness-of-fit. Non-normal distributions were *ln* (natural logarithm) transformed to meet criteria for parametric statistical analysis. One-way analysis of variance (ANOVA) was used to test for significant differences in mean maximum thaw depths in the three SEEDS treatments. When significant differences existed, multiple comparison testing (Tukey's test) was used to isolate the differences between groups. Both *pairwise* and *vs.control* testing was used.

Results:

Seasonal post-fire moisture content and differences from the control treatment.

In 1997, during the spring coring period, the majority of samples exhibited some type of visible ice, generally comprised of small crystals or flakes. In a few isolated cases, longer (7-8 cm long) core segments were entirely comprised of "clean ice" (Appendix A). These ice layers were observed in cores originating from the burned forest and the ROW's. No ice lenses/veins were encountered during coring of the trench sites, although small ice crystals, were seen . In the control area, no ice lenses, were encountered. During the late summer coring period, ice of any type (veins, interstitial, etc.) was conspicuously absent from cores extracted from the ROW sites. Cores for this period usually did not exceed ~150 cm. These were entirely within the active layer. However, frozen silts and individual ice crystals were present in cores from the burned forest, where they penetrated the permafrost table. All cores exhibited high amounts of excess free water in the upper 90-100 cm. The only exception was the control treatment where excess water was present in the upper 53 cm of the soil column (Figure 3-2 D) (Table 3-1).

The burned forest exhibited maximum moisture content in the upper 60 cm where moisture varied between 72% and 30%. Below 60 cm, moisture content remained between 20% and 40% (Figure 3-2 A). The upper 10 cm were 3% dryer than the control. However, between 20-110 cm, moisture content was at least 12% higher than the control (Table 3-2).

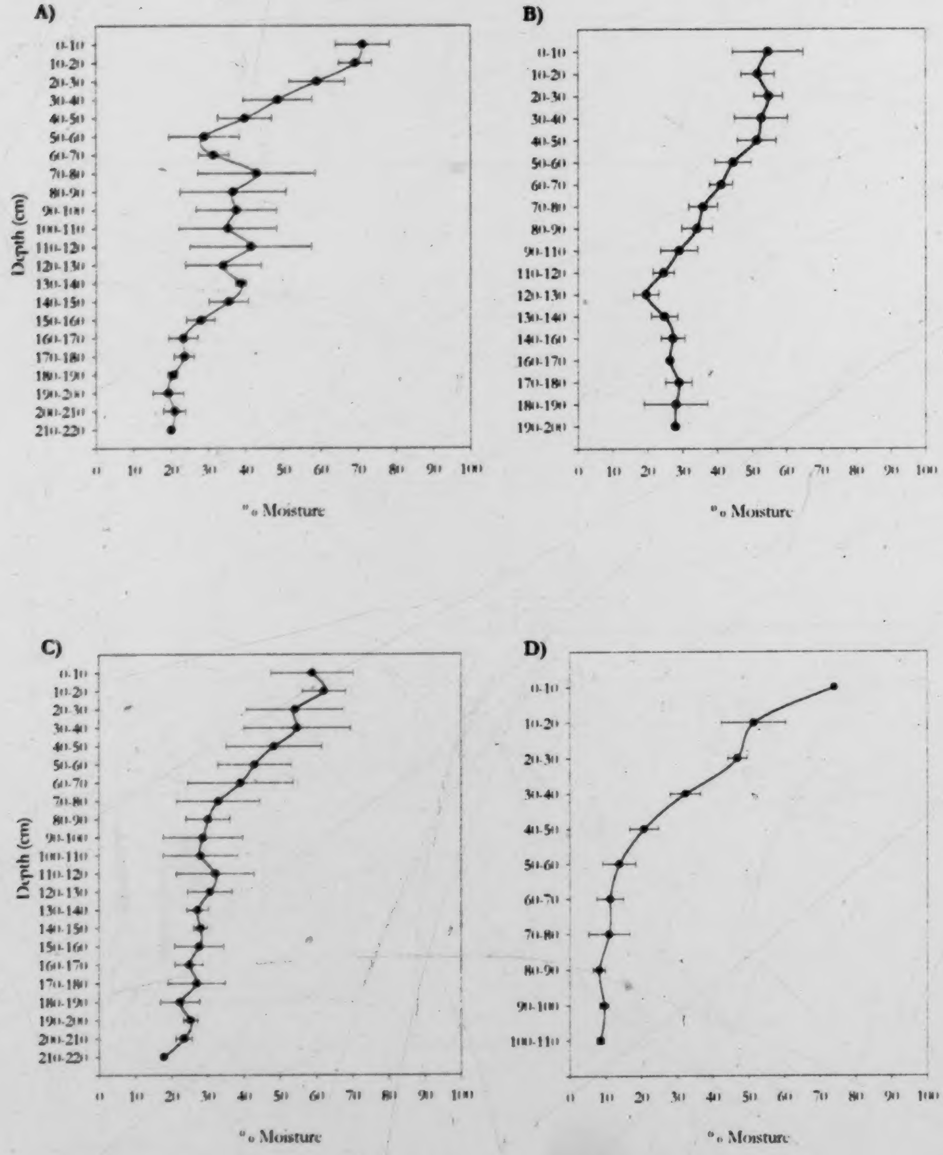

Figure 3-2: 1997 post-fire mean soil moisture contents in **A)** Burned Forest treatment, **B)** ROW treatment, **C)** Trench treatment and **D)** Control treatment. Circles represent mean values and error bars represent standard deviation.

Mean Moisture Contents (%)											
ROW			Trench			Burned Forest			Control		
Depth (cm)	Mean	Std.Dev.	Depth (cm)	Mean	Std.Dev.	Depth (cm)	Mean	Std.Dev.	Depth (cm)	Mean	Std.Dev.
10	54.6	10.2	10	58.9	11.3	10	71.0	7.2	10	74.0	0.0
20	51.7	4.8	20	62.2	6.0	20	69.1	4.3	20	51.4	9.0
30	54.8	4.2	30	54.1	13.2	30	58.9	7.4	30	46.8	2.7
40	52.7	7.7	40	54.8	14.7	40	48.4	9.1	40	32.3	4.2
50	51.4	5.6	50	48.3	13.2	50	39.6	7.2	50	20.8	4.0
60	44.6	5.2	60	43.0	10.1	60	28.8	9.3	60	13.8	4.6
70	41.1	3.3	70	39.1	14.5	70	31.4	4.0	70	11.3	3.7
80	36.0	4.1	80	33.0	11.5	80	42.8	15.6	80	11.0	5.8
90	34.2	4.4	90	30.1	6.0	90	36.5	14.1	90	8.2	1.6
110	29.0	5.3	100	28.8	10.9	100	37.5	10.6	100	9.6	1.2
120	24.6	3.0	110	28.1	10.3	110	35.2	13.0	110	8.6	0.9
130	19.6	3.6	120	32.2	10.6	120	41.3	16.2	--	-	-
140	24.8	3.8	130	30.7	6.1	130	34.0	10.1	-	-	-
160	27.3	3.4	140	27.3	2.9	140	38.7	1.3	-	-	-
171	26.4	0.1	150	28.1	1.9	150	35.4	5.2	-	-	-
180	29.0	3.8	160	27.7	6.7	160	28.0	3.8	-	-	-
190	28.1	9.1	170	24.9	3.9	170	23.3	3.9	-	-	-
195	28.0	0.0	180	27.0	7.9	180	23.6	2.6	-	-	-
-	-	-	190	28.1	9.1	190	20.5	1.1	-	-	-
-	-	-	195	28.0	0.0	200	19.3	4.1	-	-	-
-	-	-	-	-	-	210	20.9	2.9	-	-	-
-	-	-	-	-	-	220	20.0	0.0	-	-	-

Table 3-1: 1997 post-fire mean moisture content for the SEEDS treatment and the control treatment.

Depth (cm)	Treatments		
	Burned Forest	ROW	Trench
10	-3	-19	-15
20	18	0	11
30	12	8	7
40	16	20	22
50	19	31	28
60	15	31	29
70	20	30	28
80	32	25	22
90	28	26	22
100	28	no data	19
110	27	20	20

Table 3-2: 1997 post-fire differences in moisture content (%) between the burned treatments and the control at various depths.

In the ROW cores, maximum moisture contents reached 56% in the top 50 cm (Figure 3-2 B). A steady decrease followed to a depth of 140 cm (20% moisture). ROW moisture in the upper 10 cm was 19% less than the control (Table 3-2). Below 20 cm, ROW cores were wetter than control. The maximum difference occurred at 60 cm depth (31%)(Figure 3-2 B).

In the trench, moisture contents decreased more rapidly than for the ROW. A maximum moisture content of 66% was recorded at 20 cm and decreased to 29% at 110 cm (Figure 3-2 C). The upper 10 cm of the trench were 15% dryer than the control. Below 20 cm, moisture contents exceeded the control values by at least 7% (Table 3-2).

The newly-established control treatment had moisture contents that steadily decreased with depth. Maximum moisture was 74% in the upper 10 cm (Figure 3-2 D). Surface moisture (0-10 cm) was greater than all burned treatments. However, below 20 cm, the control treatment had lower moisture contents than the burned treatments (Table 3-2).

Pre- vs.post-fire changes in moisture content.

The small sample sizes obtained from soil coring did not permit rigorous statistical testing of the data. Nonetheless, a graphical representation of the results permitted visual assessment. Following fire, moisture contents generally decreased for ROW and burned forest treatments while there was an increase in the trench (Figure 3-3). For all three burned sites, moisture content in the upper 15 cm decreased by at least 10% from pre-fire values. In the 15-30 cm depth range, moisture contents for ROW and trench were again lower than in pre-fire conditions (-11% and -5% respectively), whilst only the burned forest had increases in moisture content.

		1986	1987	1988	1989	1990	1991	1992	1993	1996	1997	1997*
Mean (cm)	**Pre-Burn Control**	39.2	50.1	56.7	59.6	59.9	63.7	67.2	71.1	-	-	-
	ROW	50.3	65.2	83.1	84.9	93.0	110.4	126.1	120.0	112.6	136.4	243.9
	Trench	70.3	103.6	132.8	163.4	149.0	167.6	164.2	158.0	112.9	156.3	245.6
	Burned Forest	-	-	-	-	-	-	-	-	82.4	92.7	120.7
Standard Deviation	**Pre-Burn Control**	9.9	11.2	12.5	13.4	15.6	17.5	27.4	31.1	-	-	-
	ROW	11.9	15.6	24.7	23.5	29.4	20.9	46.0	44.8	49.0	34.5	-
	Trench	13.6	18.8	25.3	24.0	17.6	31.5	26.1	28.4	46.5	31.3	-
	Burned Forest	-	-	-	-	-	-	-	-	27.5	29.0	-
Yearly Increase (%)	**Pre-Burn Control**	-	27.7	13.0	5.1	0.5	6.2	5.6	5.7	-	-	-
	ROW	-	29.7	27.3	2.1	9.6	18.7	14.2	-4.8	-6.2	21.1	-
	Trench	-	47.3	28.2	22.9	-8.8	12.5	-2.0	-3.8	-28.6	38.4	-
	Burned Forest	-	-	-	-	-	-	-	-	15.9	11.1	-
Increase from 1986 (%)	**Pre-Burn Control**	-	27.7	44.5	51.9	52.8	62.3	71.4	81.2	-	-	-
	ROW	-	29.7	65.2	68.7	85.0	119.5	150.7	138.7	123.9	171.3	268.3
	Trench	-	47.3	88.9	132.4	111.9	138.4	133.6	124.8	60.5	122.3	249.4
	Burned Forest	-	-	-	-	-		-	-	110.0	136.3	207.7

1997* represent values corrected for surface subsidence

Table 3-3: Mean maximum thaw depth, standard deviation, yearly increase and total increase since 1986 for the SEEDS treatments. Data from 1986-1991 are from Nolte (1991), 1990-1996 are from Kershaw (unpublished).

Below 30 cm, trench moisture content was greater than pre-fire values. A maximum increase of ~18% was reached in the 105-120 cm depth range (Figure 3-3). The burned forest had lower post-fire moisture contents below 45 cm depth. A maximum decrease of ~12% was attained in the 60-75cm range. Finally, post-fire moisture in the ROW cores decreased throughout the soil column. Below 60-75 cm, moisture content was similar to pre-fire conditions with differences of -3% to 0.8%.

Post-fire seasonal variations in mean maximum thaw depth.

In 1996, mean maximum thaw depth for the burned forest, ROW and trench were 82 cm, 113 cm and 112 cm respectively (Table 3-3) (Figure 3-4). In 1997, mean maximum thaw depth had increased to 93 cm for the burned forest, 136 cm for the ROW and 156 cm for the trench. This constituted an increase of 11% for the burned forest, 21% for the ROW and 38% for the trench over the 1996 values (Table 3-3) (Figure 3-4). Thaw depth was 143%, 211% and 241% greater than the control for the burned forest, ROW and trench treatments respectively. A series of t-tests were used to compare thaw depths between treatments for both post-fire thaw seasons. In order to compare the two datasets, the last probing of 1996 (7 August) and the second-last probing of 1997 (8 August) were used. There were significant differences in thaw depth for burned forest and trench sites. No significant difference existed between years on the ROW (Table 3-4).

Treatments	t	D.F.	p	Sign.Difference
Burned Forest 1996 vs. Burned Forest 1997	2.32	135.00	0.02	Yes
ROW 1996 vs. ROW 1997	2.00	41.00	0.05	No
Trench 1996 vs. Trench 1997	3.47	38.00	0.001	Yes

Table 3-4: Results of *t-test* comparing thaw depths of each burned treatment for the years 1996-1997. Values are *ln* (*natural log.*) transformed. 1996 data are from Kershaw (unpublished).

Pre- vs. post-fire variations in mean maximum thaw depth.

All post-fire SEEDS treatments had increases in active layer depth. The 1997 probe depths were corrected for surface subsidence, thereby increasing the absolute thaw depth values. When compared to 1986 values, mean maximum thaw depths for 1997 were 243.3%, 258.8% and 203.3% greater for the burned forest, the ROW and the trench respectively (Table 3-3).

One-way analysis of variance (ANOVA) revealed significant differences in mean maximum thaw depth among all three treatments ($p<0.001$) during post-fire years (Table 3-5). Subsequent multiple comparison testing revealed significant differences between thaw depths in trench and

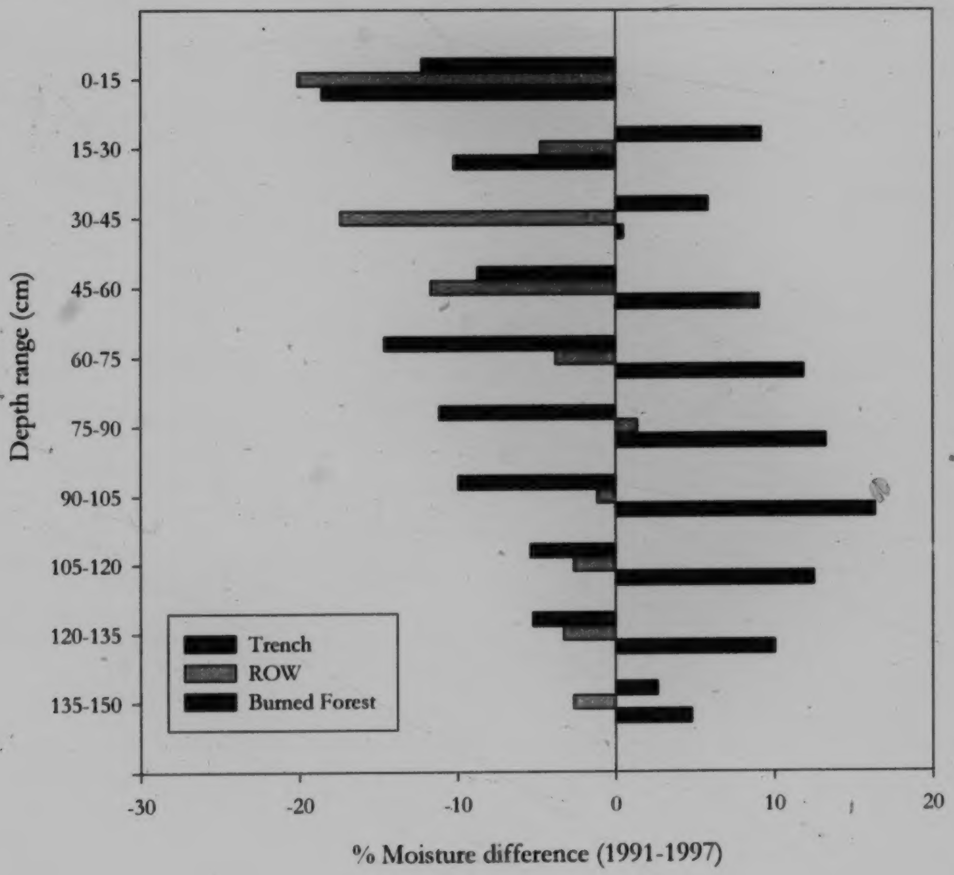

Figure 3-3: Differences in mean soil moisture contents between 1991 (Nolte 1991) and 1997 for the SEEDS treatments

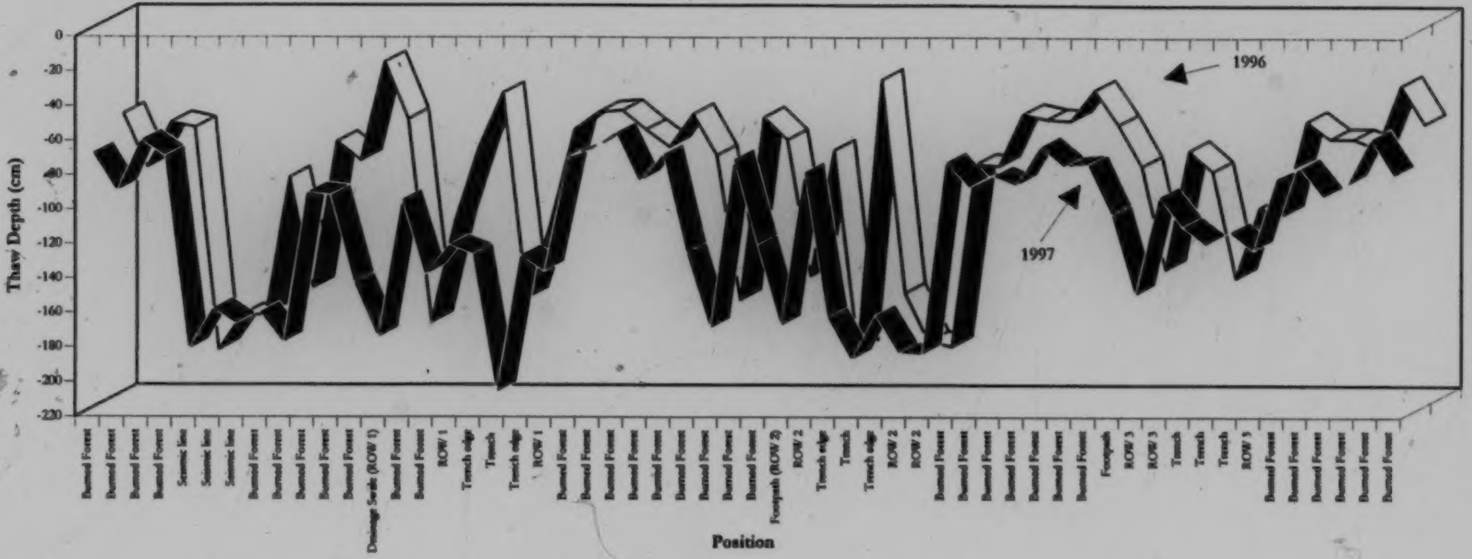

Figure 3-4: Mid-August thaw depth at the SEEDS site during the two post-fire years of measurement. Plotted values are averaged over the two probe transects. 1996 data are from Kershaw (unpublished).

burned forest sites and between ROW and burned forest treatments ($p<0.05$) (Table 3-6). No significant difference existed between trench and ROW treatments. In 1997, subsidence-corrected values as well as raw values were used for testing. In both cases, patterns similar to that observed in 1996 emerged: pairwise testing of ROW vs. burned forest as well as trench vs. burned forest revealed significant differences in thaw depths whilst no significant difference existed between ROW vs. trench pairs.

Source of variation	D.F.	S.S.	M.S.	F	p
Between	4	2.851	0.713	5.862	<0.001
Residuals	95	11.552	0.122		
Total	99	14.403			

Table 3-5: *ANOVA* results comparing 1997 mean maximum thaw depths among Burned Forest, ROW, Trench and Control treatments. Values are *ln* (*natural log.*) transformed.

Treatments	Difference of Means	P	q	$p<0.05$
Trench vs. Control	0.927	4	16.327	Yes
Trench vs. Burned Forest	0.545	4	9.982	Yes
Trench vs. ROW	0.15	4	2.257	No
ROW vs. Control	0.777	4	14.16	Yes
ROW vs. Burned Forest	0.395	4	7.509	Yes
Burned Forest vs. Control	0.382	4	9.559	Yes

Table 3-6: Multiple comparison test (*Tukey's test*) for pairs of mean maximum thaw depths in the three burned treatments (Burned Forest, ROW, Trench) and the Control treatment. All comparisons are based on *ln* (*natural log.*) transformed data.

Discussion:

The graphic representation of the active layer in late summer (1996-1997) indicated that patterns of thaw were relatively constant during these two post-fire years. The principal difference being the magnitude of thaw which was greater for the latter year. Each point on the graph represented the mean maximum thaw depth for each probe site averaged for the two transects. The years 1996 and 1997 were plotted with values that were not corrected to account for total subsidence, since these data were not available in 1996. This generalization of the position of the frost table is probably not an accurate representation of the actual field conditions. The averaging of values between transects has certainly attenuated some of the micro-site related variability of the thaw depth.

Pre- vs. post-fire changes in mean moisture content.

Following fire, the modified energy balance at the ground surface usually triggers the melting of ground ice. This is particularly pronounced in areas of thaw-susceptible, ice-rich permafrost such as that present at the SEEDS site. Associated with this melting is an expulsion of ground-ice meltwater and associated ground subsidence (Collins *et al.* 1994, Mackay 1995). The thawing of ice-rich permafrost adds water to the bottom of the active layer. This amount of water is thought to be approximately equal in volume to the amount of ground subsidence (Mackay 1995). In summer, pore water from the thawing active layer can migrate downwards under a temperature gradient and refreeze around the position of the seasonal permafrost table (Parmuzina 1978, Cheng 1982, Mackay 1983, Burn 1988, Williams and Smith 1989).This results in an increase of ground ice at these depths. This mechanism can explain the changes in moisture content observed at the SEEDS site.

-Post-fire differences in moisture content between treatments:

The decrease of post-fire moisture content below the organic layer (<15 cm) followed the progression of the deepening of the active layer. The significant differences in moisture content between the trench/burned forest and ROW/burned forest were the result of the age of the disturbance and the time since thaw progressed beyond the pre-disturbance active layer depth. The age of the disturbance also explained the lack of signifcant differences between ROW/Trench. Both sites were affected by a disturbed energy balance for 8-9 years more than the burned forest. Because of this, permafrost melted and meltwater drained from these areas in greater amounts and for longer periods than in the burned forest.

-Post-fire differences in moisture content between burned and control treatments.

The differences in moisture between the control and burned treatments resulted from the post-fire modification of the evaporative regime as well as slight differences in the particle size distribution of soils among the sites. The moisture decrease in the burned treatments was related to the thickness and colour of the remaining organic layer. In the burned forest and the ROWs, there was a thinning of this moss/peat layer as a result of being consumed/oxydized by fire. Additionally, the decrease in albedo led to increased surface temperatures and greater rates of evaporation, thereby lowering the moisture content of these organics (Rouse and Mills 1977).

Since both of these treatments still contained their organic layer, it would be reasonable to expect similar levels of moisture within this layer. Why, then, were the moisture contents so markedly different? The greater decrease in moisture of the ROW was likely related to the near-surface ground ice content. It is important to remember that this comparison was based on two datasets collected 7 years apart and that the ROW's were undergoing permafrost degradation before the fire. Consequently, the melting of excess ground ice and the runoff of this meltwater lowered the moisture contents of the ROW treatments. The difference in pre-/post-fire moisture contents for this treatment did not indicate a large decrease. Although there is no way of evaluating the runoff that has occurred, the amount of ground subsidence observed between 1990 and 1997 (Chapter 4) confirmed that excess ice has been removed. In the trench, the organic layer was eliminated during construction and cannot be invoked as a controlling factor on near surface moisture contents. As was the case for the ROW's, ground subsidence suggested that excess ice melted from the upper soil column, partly explaining the lowered post-fire moisture contents for these depths. More likely, the lower post-fire moisture was a result of a sampling bias. During coring, core segments could not be extracted from water-logged areas as suction developed because of meltwater filling the whole. This restricted coring to elevated (and therefore dryer at the surface) sites within the trench where a core hole could be started without collapsing. As this was the only way of extracting cores from the trench, the method had to be used despite the bias. This explains the presence of lower moisture in the top 10 cm of the trench.

Below 20 cm, all burned treatments were wetter than the control as a result of a difference in particle size. The SEEDS treatments were composed primarily of silts and clays, sometimes containing fine to coarse sand (Appendix A). In the control treatment, the silt-clay fraction was lower and coarse sand was more abundant. The finer material in the burned treatments offered optimal conditions for water saturation and the development of segregated ice. The poor drainage imparted by these material types favoured higher moisture in the SEEDS treatments.

Pre- vs. post-fire variations in thaw depth.

Burned Forest/ Pre-fire Control

Since the creation of the SEEDS site in 1986, there have been significant differences in thaw depths among the three treatments (Gallinger 1990, Nolte 1991). In 1989, the control forest (undisturbed by clearing) had attained thaw depths that were almost 20 cm deeper than the 1986 measurement. Nolte(1991) and Seburn (1993) reported an apparent stabilizing trend for the forest sites as early as 1988. This stabilization was relatively constant from 1989-1992. Seburn (1993) reported no significant change in mean maximum thaw depth for this period. The initial increase in thaw depth (1986-1987) may have been a product of the establishment of the first probe networks where localized footpaths developed. This resulted in a compaction of the surface organic cover, thereby increasing the bulk density and thermal conductivity of the soil (Goodrich 1983, Lawson 1986). This would seem plausible, more so since the same footpaths were still visible following the fire. An increase in thaw depth in the burned forest was recorded during the two thaw seasons following fire. In 1996, thaw depth reached 82 cm, an increase of 23% over the last recording (1992) and 91% over the initial 1986 values. In 1997, thaw depths reached 93 cm, representing an increase of 37% over the 1992 pre-fire probing. These values did not take into account surface subsidence at the site. Only the 1997 values could be corrected for subsidence. Mean subsidence in the forest was calculated at 28 cm (Chapter 4). Mean subsidence-corrected thaw depth became 121 cm, representing a 208% increase over the 1986 thaw depths. Since subsidence has most likely been ongoing at different temporal and spatial rates, only a comparison with pre-clearing values is valid. The lack of data on the degree of subsidence that has occurred annually between 1987 and 1996 renders any comparison with 1997 data precarious. However, given the reduced rate of thaw depth increase and the lower moisture content with depth, it may be safe to assume little subsidence between 1990 and 1995 prior to the fire. If one accepts this, then all increases in thaw depth were due to the 1995 wildfire and took place over three thaw seasons.

The post-fire increase in thaw depth was not unexpected. The disturbance created by the fire modified the energy balance of the surface and the resulting increase in thaw depth was an expression of these microclimatic modifications. The 1995 fire did not consume all of the organic mat. The degree of burn was variable throughout the site and an organic layer (10-15 cm thick) remained in the forest and on parts of the ROWs. The principal modification to this surface was a substantial increase in albedo (Chapter 2). The insulating properties of the organic mat have been discussed by numerous authors (Luthin and Guymon 1974, Zoltai and Tarnocai 1975, Riseborough and Burn 1988) who agreed that the persistence of sporadic and some discontinuous permafrost was closely related to the thickness and moisture content of these organics. Following fire, decreased albedo and increased moisture contents due to ground ice melting have increased the thermal conductivity of this layer in the early part of the melt season (Farouki 1986, Kane *et al.* 1975), resulting in the observed increased thaw depths. Additionnally, this increased thaw depth was linked to the removal of the tree canopy and the ensuing increase in incoming shortwave radiation. The open-canopied forest present before fire was completely removed. Although sparse, the pre-fire tree cover buffered the incoming radiation by possibly absorbing and/or reflecting between 40%-76% of this shortwave radiation (Chapter 2) (Haag and Bliss 1974a, Lafleur and Adams 1986, Rouse and Mills 1977).

Rights-of-way

Immediately after clearing, Gallinger (1990) found that mean maximum thaw depth increased from 1986 to 1989. From 1989 to 1991, Seburn (1993) also found an increase in mean maximum thaw depths. Probe data from 1992-1993 (Kershaw, unpublished data) were again indicative of thaw depth increases. This suggested that the permafrost was still degrading eight years after the initial disturbance. In 1996 (Kershaw, unpublished data)-1997, there was again an increase in thaw depths.

The lack of signifcant differences in thaw depth after 1991 was reported by Seburn (1993). He noted that the 1990 mean maximum thaw depth was ~10 cm deeper than the previous year. However, this was not a significant difference ($p<0.01$). In 1991, the ROW attained its greatest mean maximum thaw depth, over 15 cm deeper than 1990. This constituted a significant difference from the 1990 thaw depths ($p<0.01$), prompting him to suggest that the permafrost was still degrading five and six years after ROW creation. (Seburn *et al.* 1996)

The post-fire active layer thickening of the ROW's indicated that permafrost degraded since 1986 and that the 1995 fire had not accelerated the rate of degradation to levels greater than those observed in 1991. The lack of significant difference between mean maximum thaw depth beyond 1991 suggested that the annual progression of thaw on the ROW's had stabilized and remained relatively constant even after fire.

A rapid increase in thaw depth was noted from 1986 to 1990 as a result of the clearing disturbance (Nolte 1991, Nolte and Kershaw 1998). During ROW clearing, the surface organic mat was not removed but was trampled to various degrees (Kershaw 1988). The initial increase between 1986-1991 was probably the result of a rapid response to this thermal disequilibrium. The organic mat buffered some of the effects of this new energy balance, resulting in a rapid (4-5 year) stabilization of the annual increase of thaw depth. Following fire, the organic layer on the ROW's was in a state similar to that observed in the burned forest. The lack of significant increase in mean maximum thaw depth stemmed from the fact that the post-fire microclimatic disturbance was not great enough to overwhelm the initial effect of the clearing disturbance. An increase in near-surface soil temperatures was observed following fire (Chapter 2) but the thermal "inertia" of the thawed material of the active layer likely dampened and bufferred (Lunardini 1981, Williams and Smith 1989) any warming that could potentially increase thaw depths.

Trenches

From the time of the first measurements taken at the SEEDS site, it was clear that the trenches were experiencing the greatest increases in mean maximum thaw depth. From 1986 to 1989, mean maximum thaw on the trenches increased at a rate of at least 20 cm a^{-1} (Nolte 1990). A temporary period of apparent permafrost aggradation was reported in 1990 when thaw depths were shallower than the previous year by 14 cm. Seburn (1993) attributed this variation to cooler and dryer climatic conditions, as recorded at Norman Wells, NWT. From 1991 to 1997, thaw depths remained relatively constant. Some caution must be exercised when interpreting these data. In 1993, the maximum thaw depth was not recorded at all probe sites. In particular, data were missing from the trench and probe lines 3 and 4. This resulted in mean values based on approximately ¼ of the total probe sites. In 1996, the final probing was performed on 7 August, the earliest of all probe dates since 1986. It was reasonable to expect that some post-survey thawing occurred; as these values were certainly an underestimation of the maximum thaw depth. Nonetheless, a pattern was apparent for the trench sites. The significant differences in mean maximum thaw depth for the years 1993 and 1996 may have occurred because of the smaller dataset. Seburn (1993) and Gallinger (1990) suggested that permafrost degradation was decreasing as early as 1989-1990 and that thaw depths in the trench were stabilizing. The post-fire thaw depth results supported this initial observation. More importantly this indicated that the fire had a very limited effect on the thaw depths of the trenches. It is probable that the initial clearing and trenching disturbed the surface to a degree far exceeding the disturbance level of the wildfire. During trenching, the surface organic mat was completely removed and subsequently back-filled, leaving bare mineral soil at the surface. This type of surface disturbance was ranked amongst the most damaging to permafrost (Hegginbottom 1973). Hegginbottom (1973) also indicated that the wildfire disturbance was much less severe than the trenching. The removal of this important thermal buffering layer, resulted in increased rates of soil heat flux and rapid thaw progression during the first 2-3 years (Nolte 1991). Similar results have been found by Hegginbottom (1973) and Viereck (1982). Both studied post-fire thaw depths following the 1968 Inuvik fire (Hegginbottom) and a fire in Alaska (Viereck). They reported thaw depths up to 50-80% deeper in areas disturbed by the construction of firebreaks in comparison to areas affected by wildfire. They concluded that the removal of the surface vegetation and the soil compaction from repeated passage of heavy machinery resulted ingreater disturbance than the fire itself. Lawson (1986) also found similar results by using a *Severity index (Si)* to quantify the degree of perturbation on areas affected by disturbances of varying degrees. Trampled vegetation had the lowest severity index and after 30 years, these areas had *Si* values that were equal or less than before disturbance. Areas of killed vegetation had values equal to or slightly higher (10%) than for pre- disturbance conditions. Sediment and vegetation removal created increases in thaw depth of 10-250% (Lawson 1986). The rates of increase observed at SEEDS fall within the upper range of Lawson's (1986) predicted values.

Spatial variation of thaw depth and influence of microsite characteristics

Microsite characteristics have often been recognized as determining factors influencing thaw depths. In particular, the ponding of water in surface depressions has been shown to increase thaw depths dramatically (Linell and Tedrow 1981, Nelson and Outcalt 1982, Swanson 1996). The importance of this fluvio-thermal erosion was invoked by Gallinger (1990) as a means of explaining the high variability of thaw depths obtained at different sites. Water accumulations were found to preferentially occur in areas affected by clearing. Post-clearing surface changes resulted in the settling and compaction of the back-filled trench materials which lead to linear depressions comprising sections of ponded or occasionally flowing water. Because the trenches were lower than surrounding areas, they collected meltwater, snowmelt and precipitation runoff preferentially. In post-fire conditions, numerous areas of ponded water were observed in the burned forest, while less were present on the ROWs. Assuming that a great deal of the variability in thaw depth was controlled by these areas of ponded water, the degree of skewness for each site was used as a way of evaluating the change in distribution variability. The degree of skewness from 1986 was used as "control" values for pre-disturbance variability to which post-disturbance/post-fire variability could be compared. From 1986 to 1993, all three SEEDS treatments had distributions that were skewed to greater degrees than in pre-fire conditions. Following fire, skewness decreased to pre-fire levels or less. This was particularly striking on the ROW where 1993 skewness was 2.064 and 1996-1997 skewness was 0.782 and -0.00741 respectively. This suggested that the variability in the distribution of thaw depths had decreased, likely as a result of surface subsidence and flattening of the ROW surfaces, resulting from the melting of ground-ice. In the burned forest, increased distribution variability was observed until 1992. Variability then decreased slightly in 1993. Post-fire data showed that variability decreased almost to pre-disturbance levels. This post-fire change may have been the result of a rapid initial response of the burned forest to the new energy balance. This process may be similar to that observed in the trench between 1986-1987, where variability had decreased rapidly after the first year, as a result of the substantial energy balance change following clearing. A rapid geomorphic response was also observed by Cody (1964), where surface subsidence in hummocky terrain occurred only 4 years after fire, as a result of ground ice melting.

Conclusion:

Following the 1995 wildfire, active layer response was variable throughout the SEEDS site. The trench sites had the least post-fire active layer increases, followed by the ROW sites and the burned forest. The trench sites were little affected by the wildfire as thaw depths were not significantly different from the last pre-fire measurements and the 1996 values. This suggested two possibilities: *i)* that the initial 1986 clearing and trenching process disturbed the surface to a greater degree than the wildfire disturbance or *ii)* that the effects are still being felt and the full response has yet to be registered. The majority of the active layer depths observed in 1997 were a result of the initial simulated transport corridor disturbances and likely occurred between 1986 and 1995. The ROW sites had low increases in active layer depths. The post-fire active layer depths were not significantly different from depths observed after 1991. Again, this absence of significant increase likely stemmed from the degree of disturbance of the initial clearing of the ROWs, that superseded the microclimatic modifications caused by wildfire. The burned forest sites had significant increases in thaw depths. This was a result of the modification of the surface energy balance resulting from the burning of the organic mat and the removal of the tree canopy. This allowed thaw to progress deeper into the ground.

Mean moisture contents have decreased at all sites following wildfire. Additionally, there has been an increase in the variability of moisture throughout the soil column. All SEEDS treatments exhibited decreased moisture contents in the upper 15 cm. This was attributed to the burning of a portion of the organic mat and its decreased albedo which favoured greater rates of evaporation. At depths below 15 cm, moisture contents were again lower than in pre-fire conditions but there were rapid fluctuations in these amounts. These fluctuations were interpreted as ephemeral active layers that resulted from the migration of water to the freezing front during each thaw season. Such areas of supersaturated material were thought to be artifacts of the progression of thaw following the wildfire.

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Chapter 4: Thermokarst subsidence and seasonal /long-term terrain modifications following wildfire and anthropogenic disturbance.

Introduction:

Surface subsidence as a result of thaw settlement constitutes one of the principal considerations in northern engineering and exploration projects. In regions of ice-rich, thaw-susceptible permafrost, surface subsidence may follow disruption of the ground. Thawing may be initiated as a result of geomorphic, vegetational or climatic modifications affecting the thermal equilibrium.

The magnitude of ground subsidence depends primarily on the severity of the initial disturbance as well as the amount and distribution of excess ice (French 1976, Williams and Smith 1989). The thawing of ground ice involves an initial reduction in volume of 9%, usually followed by an additional loss due to drainage of meltwater (Williams 1982). The ultimate amount of settlement will depend on the effective stress between soil particles, which in turn is a function of the static overburden pressure and the final pore water pressure (Williams and Smith 1989).

A common manifestation of surface subsidence is the development of thermokarst depressions following rapid increases in thaw depth. Williams and Smith (1989) noted that surface subsidence could be a positive feedback mechanism when it allowed thawing to progress deeper, leading to more subsidence. As thermokarst develops, water accumulation in surface depressions can substantially increase thawing depths (Kerfoot 1973, Swanson 1996).

Past studies of wildfires and permafrost have reported varying rates of surface subsidence. Following the 1968 fire at Inuvik, Northwest Territories, in a region of continuous permafrost, Hegginbottom (1971) noted subsidence of 19 cm. This was coupled with a flattening of the microrelief as hummocks generally became less pronounced. Additionally, the buldozing of the surface during fire-break construction caused 28 cm of subsidence. Viereck (1982) also reported substantial surface subsidence following firebreak construction. Ten years after the Wickersham Dome fire in Alaska, surfaces underlain by discontinuous permafrost had subsided by as much as 60 cm.

Surface subsidence on linear disturbances:

Following the construction of the Norman Wells pipeline, a monitoring program was undertaken to improve impact evaluation and mitigation in permafrost terrain (Burgess and Harry 1989). These authors reported pronounced settlement within the trench along as much as 30% of the 869 km pipeline route. Also, a number of small, near-circular thermokarst pits and ponds up to 3 m in diameter had developed on the pipeline right-of-way (ROW) surface. On level stretches of terrain, trench subsidence led to ponding within shallow linear basins, while on sloping ground it facilitated water flow and erosion along the ditch line (Burgess and Harry 1989). In the pipeline trench, the maximum recorded settlement was over 50 cm at 14 of 17 surveyed sites, with three of these having a maximum settlement of 100 cm or more. Along the ROW, maximum settlement of 50 cm or more was observed at 8 sites (Burgess and Harry 1989).

At the SEEDS site, seasonal subsidence rates reported by Nolte (1991) reached 9 cm and 12 cm for the ROW and trench respectively. Mean total subsidence, 4 years after disturbance, attained 31 cm and 58 cm for the ROW and trench respectively (Nolte 1991).

Ground penetrating radar as a tool for geophysical investigations:

Ground penetrating radar (GPR) surveying has been shown to be a fast, reliable and relatively inexpensive technique for non-destructive, high-resolution mapping of subsurface materials to depths of 3-30 m, depending upon the electrical properties of the materials (Davis and Annan 1989). These qualities have extended the use of GPR surveying to a wide range of disciplines. The technique has been used in applications such as fracture mapping (Benson and Yuhr 1990); archaeological investigations (Toshioka *et al.* 1990) and forensic applications (Strongman 1992).

In geomorphological studies, GPR has been used in the mapping of subsurface stratigraphy (Davis and Annan 1989, Jol and Smith 1991, Smith and Jol 1992, Moorman *et al.* 1991). It was quickly recognized that GPR operated optimally in mapping the stratigraphy and ice content of coarse-grained, perennially frozen sediments. Coarse-grained deposits containing massive ground ice have been surveyed by Dallimore and Davis (1987, 1992), Robinson *et al.* (1992, 1993), Barry and Pollard (1992) and Wolfe *et al.* (1997). GPR techniques have also been used extensively to map permafrost (Annan and Davis 1976, Seguin *et al.* 1989, Judge *et al.* 1991, Pilon *et al.* 1979, 1992) and active layer characteristics (Pilon *et al.* 1985, Doolittle *et al.* 1990). Finally, GPR was used in geotechnical investigations of slopes along the Norman Wells pipeline (Burgess *et al.* 1995, Moorman *et al.* 1995).

Objectives:

The objectives of this study were:

i) Evaluate post-fire seasonal subsidence in a subarctic upland forest underlain by discontinuous permafrost.

ii) Evaluate total surface subsidence since ROW clearing (1986) and since the last topographic survey (1990).

Methods:

Topographic Survey:

Seasonal and longer-term subsidence was determined by leveling. Two surveys were conducted in 1997. The first survey was conducted over a period of four days (2-6 June), as close to the onset of thaw as possible. The second survey was carried out between 7-10 August. For logistical reasons, this survey was carried out before the maximum thaw depth was reached. A total of 1050 points were surveyed each time. Points were numbered and marked with pin flags to facilitate the second survey. A total of 43 points could not be relocated during the second survey. Surface elevation was measured to the nearest centimeter, using a Sokkisha B2 Automatic level. During each siting the bearing of each point was recorded. Elevations and bearings were transferred to a grid producing a triplet (x,y,z) of coordinates to produce contour maps and digital elevation models (DEMs).

For both spring and late summer surveys, all elevations were measured from a pre-established benchmark at the SEEDS site. This benchmark was established and used as a datum in 1990 during a similar exercise (Nolte 1991). The datum consisted of three wooden dowels placed in a triangle, 1.5 m apart and anchored to the permafrost (Nolte 1991). Although the dowels were partially burned, enough stock remained to re-establish the benchmark in 1997. Closing errors were corrected according to the benchmark using standard techniques. The range of error was believed to be within 2.5-3 cm.

From the 1050 survey points,

575 were located in the burned forest,
239 were located on the ROWs and adjacent ROW connectors
106 were located in the trenches
40 were located along the 1975 seismic line
30 were located in the newly-established, post-fire control.

Ground Penetrating Radar:

A total of three GPR transects were surveyed in 1997. These were established in order to adequately represent the various SEEDS treatments (Figure 4-1). The GPR data were collected using a PulseEKKO IV GPR system (manufactured by Sensors & Software Inc.) with a 400 Volt transmitter and 100 MHz antennae. A constant antenna offset (separation) of 1 m was used in conjunction with a 0.25 m step size. A stacked pulsed radar signal of 32 source excitations was used to improve the signal-to-noise ratio (Fisher *et al.* 1992 a, b). Signal propagation velocities were computed from common midpoint surveys (CMP) and were checked with published results (Barry and Pollard 1992, Seguin *et al.* 1989).

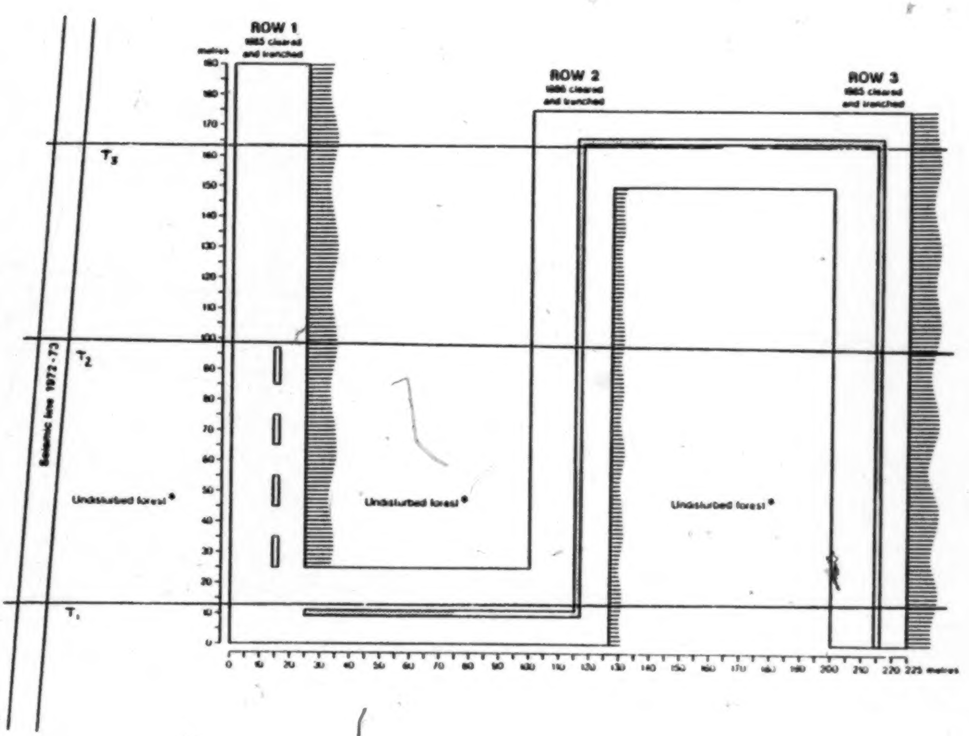

Figure 4-1: Map of SEEDS research site and location of Ground Penetrating Radar (GPR) transects. Modified from Kershaw (1991).

Data processing:

Topographic data

The series of data triplets were used to produce two color-classed, hill-shaded digital elevation models (DEM) of seasonal and longer-term ground subsidence. DEMs were produced using three programs from the TERRA FIRMA cartography software. The program QSURF was first used to interpolate and generate a grid of surface elevations. This yielded a grid composed of 565 rows and 645 columns for the longer-term subsidence model, and a grid of 735 rows and 865 columns for the seasonal subsidence model. In both cases, a grid cell size of 0.5 m was used. Secondly, the LIGHT program was used to create a relative radiance file, consisting of a hill shading of each surface. Finally, the output files generated in the two previous steps were integrated into a single hill-shaded, color-classed surface model. The color pallet used in the classification was devised to allow three-dimensional viewing.

Statistical analysis:

The Kolmogorov-Smirnov normality test revealed that subsidence data were not normally distributed. The data were *ln* (*natural logarithm*) transformed yet the distribution remained non-normal. Consequently, non-parametric statistical tests had to be used. Comparisons of mean subsidence in the treatments was evaluated using the Kuskal-Wallis ANOVA on Ranks. When significant differences existed between the treatments, Pairwise Multiple Comparisons were performed using *Dunn's Method.*

Ground Penetrating Radar:

GPR data have the advantage of being recorded digitally, allowing for a variety of processing techniques to be applied. Data processing was performed with the pulseEKKO IV software provided by the system manufacturer. The three transects were corrected for surface elevation changes along the survey path. Additionally an SEC gain (Spreading and Exponential Compensation) and DEWOW trace corrections were applied to the data. The SEC gain was used to compensate for the spreading losses and dissipation of energy in the subsurface. This gain had the advantage of preserving the relative amplitude information from the reflectors. It allowed for reliable deductions concerning the strength of reflectors relative to others, even after corrections had been applied. The DEWOW trace corrections were applied in order to remove low frequency "WOW" signals superimposed on the high frequency reflections. Following corrections, the data files were exported into PCX file formats to facilitate their manipulation in drawing packages. Figures 4-4 through 4-8 were produced by using a combination of the Corel Draw and Adobe Photoshop software packages.

GPR data interpretation techniques:

Once GPR profiles have been plotted with the appropriate filters and gains applied, results can be analyzed. Typically, the first reflection received in each trace is called an "air wave" which travels through the air between the transmitter and the receiver. Because the propagation speed of this first wave remains constant throughout the survey, it can be used as a marker for the ground surface (Wolfe *et al.* 1997, Robinson *et al.* 1993). The second signal received is the ground wave, traveling directly from the transmitter to the receiver through the upper surface "skin" of the ground. The propagation velocities through the ground are always slower than through the air and ground waves are generally recorded with a slight delay from the arrival of the air wave. However, these signals can appear as one thicker wave signal where velocities are high. The succeeding signals on the profiles are from interfaces within the ground and they are recorded in order of depth (shallowest first).

The patterns of reflections on the profiles provide clues as to the nature of the subsurface material. Continuous line returns were expected from relatively smooth, continuous interfaces (Wolfe *et al.* 1997, Robinson *et al.* 1992, 1993). Laterally continuous reflections generally appear from sediment/bedrock contacts, well-developed stratigraphy and other abrupt contacts. For the SEEDS profiles, continuous reflections could be generated by active-layer/permafrost contacts or ice/thawed sediment interfaces.

Chaotic (non-continuous) reflections may reflect the presence of thin layers of small point source reflectors of varying dielectric constants within the ground. These could include isolated coarse sediments such as cobbles or small boulders (Wolfe *et al.* 1997, Pilon *et al.* 1992, Moorman *et al.* 1991) or ice lenses (Barry and Pollard 1992). Finally, some reflections appear as combinations of chaotic and semi-continuous returns and can result from more extensive ice lenses or sediment bedding.

The subjective nature of GPR profile interpretation dictates that some ancillary data sources, such as cores or nearby exposures, be used. The 32 soil cores (Chapter 3) were used to verify radar profile interpretations. Recent GPR results have shown that certain geologic conditions often yield predictable results. Radar propagation velocities are often high (0.09-0.16 m ns^{-1}) in ice-rich frozen materials. These higher velocities enable faster pulse reflections with a higher frequency return signal to the receiver. Signal attenuation is also lessened in frozen material, resulting in deeper penetration than what would be achieved in unfrozen sediment. Inversely, propagation velocities decrease in fine-grained, unfrozen material. This causes a pulse "drag" on the profiles resulting in a thicker, smeared reflector. Certain materials are also known to attenuate signals more rapidly than others. For example, penetration in silts and clays may be limited to a few meters, perhaps slightly more if the clay is frozen (Wolfe *et al* 1997). Finally, signal penetration and resolution will depend on antennae frequency. Low frequency (25, 50 MHz) antennae allow deep signal penetration but with poor resolution of subsurface details. Inversely, higher frequency antennae (100, 200, 400 MHz) allow shallow signal penetration with a high resolution of subsurface details (Davis and Annan 1989).

Results:

Seasonal subsidence:

Comparison between treatments:

Mean seasonal subsidence in the unburned control was at least 54% less than all the SEEDS treatments (Table 4-1). The greatest difference occurred along the trench where subsidence was 276% greater than in the control (Table 4-1). Kruskall-Wallis One Way ANOVA on Ranks revealed significant differences in the seasonal subsidence of all treatments (H=376.6, d.f.=4, P=<0.001). All pairwise multiple comparison of the means also revealed significant differences among all treatments except the seismic *vs.* ROW combination of treatments (Table 4-2) (Figure 4-2).

Treatment	n size	Mean	Standard deviation
Burned Forest	472	12.54	2.89
ROW	239	14.23	3.18
Trench	105	18.7	2.34
Control	30	6.78	2.73
Seismic Line	40	15.53	2.26

Table 4-1: Mean 1997 surface subsidence for the Burned Forest, ROW, Trench, Seismic Line and Control treatments. Subsidence in cm.

Comparison	Diff of Ranks	p	Q	P<0.05
Trench vs. Control	852.19	5	14.43	Yes
Trench vs. Burned Forest	506.75	4	16.78	Yes
Trench vs. ROW	361.77	3	10.85	Yes
Trench vs. Seismic Line	239.57	2	4.52	Yes
Seismic Line vs. Control	612.62	4	8.88	Yes
Seismic Line vs. Burned Forest	267.17	3	5.72	Yes
Seismic Line vs. ROW	122.20	2	2.50	No
ROW vs. Control	490.42	3	8.87	Yes
ROW vs. Burned Forest	144.98	2	6.59	Yes
Burned Forest vs. Control	345.44	2	6.46	Yes

Table 4-2: Results of Pairwise Multiple Comparison Procedure between treatments using *Dunn's Method.*

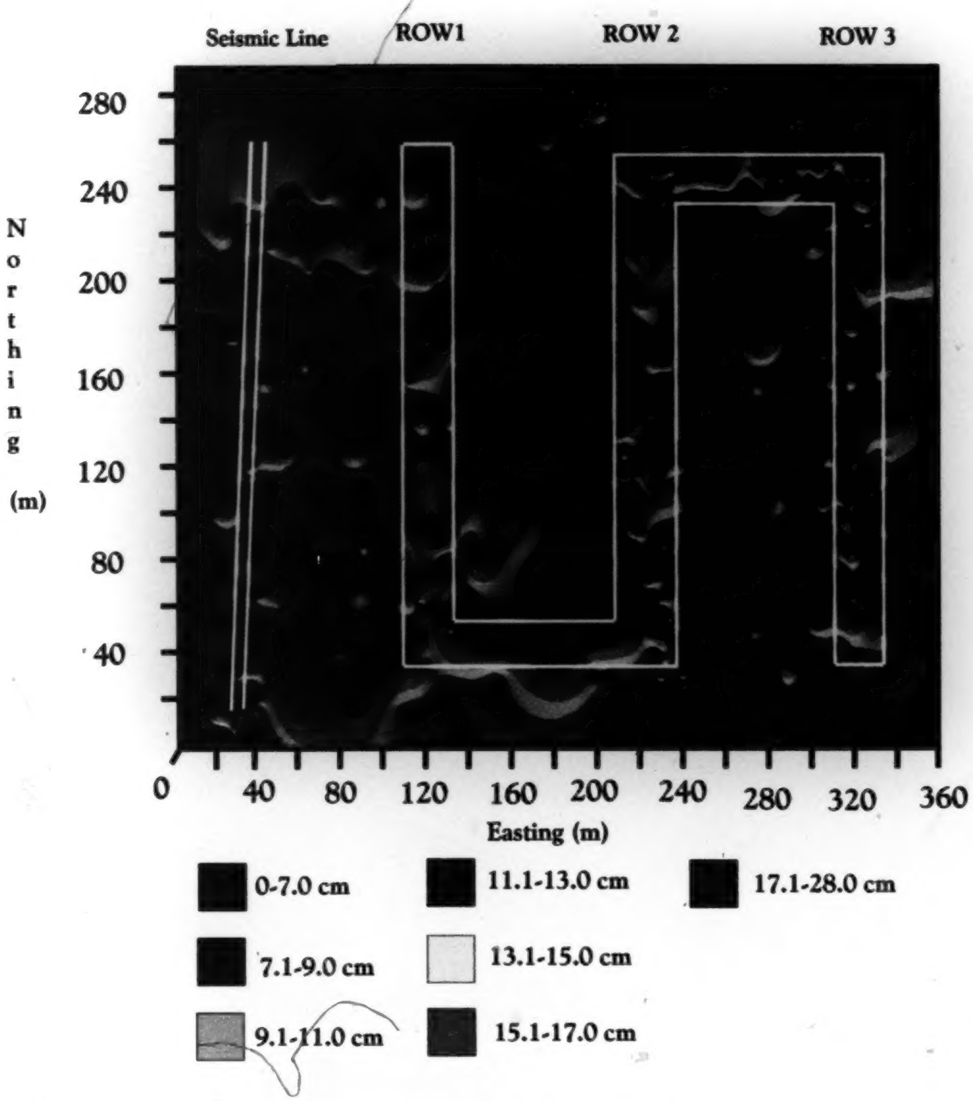

Figure 4-2: Colour-classed, hill-shaded digital elevation model of 1997 seasonal subsidence at SEEDS.

Comparison within treatments:

Mean seasonal subsidence in the burned forest was greatest in the area between ROWs 1-2 (Table 4-3). The difference with the lowest value was only 1.4 cm yet this constituted a significant difference (P<0.001) (Table 4-4). ROW 3 had the most subsidence of all ROWs (16 cm) this was 2cm and 0.8 cm more than ROWs 1 and 2 respectively (Table 4-3). However, this difference was not significant (Table 4-4). In the trench treatment, the most subsidence occurred along trench 3 closely followed by trench 2 which was 0.42 cm less. Trench 1 had the least amount of subsidence (Table 4-3). These differences were statistically significant (P<0.001) (Table 4-4).

Treatment	n-size	Mean	Standard Deviation	Maximum	Minimum
Burned Forest West	126	11.87	3.0	21.80	5.60
Burned Forest East	94	11.96	3.4	22.60	6.30
Burned Forest ROWs 1-2	145	13.27	2.6	19.50	7.40
Burned Forest ROWs 2-3	156	12.33	2.4	21.40	6.70
ROW 1	59	14.08	3.1	20.10	8.30
ROW 2	54	15.28	4.0	21.70	8.40
ROW 3	81	16.07	3.1	23.20	7.80
Trench 1	34	15.38	2.4	19.40	12.10
Trench 2	38	20.76	2.6	25.70	14.80
Trench 3	33	21.18	2.3	27.20	17.50

Table 4-3: Within treatment descriptive statistics of 1997 seasonal subsidence for the Burned Forest, ROW and Trench treatments.

Treatment	H	d.f.	P	Significant
Burned Forest	26.34	3	<0.001	Yes
ROW	0.37	2	0.832	No
Trench	56.04	2	<0.001	Yes

Table 4-4: Results of One-Way Analysis of Variance on Ranks within treatments.

Total surface subsidence since 1990:

Comparison between treatments:

Since 1990, the ROW treatment has subsided the most (32.2 cm) followed by the trench (32.1 cm) and the burned forest (24 cm) (Table 4-5).

Treatment	n size	Mean	Standard deviation
Burned Forest	472	24	11.4
ROW	239	32.2	8.7
Trench	105	32.18	7.7

Table 4-5: Mean total surface subsidence since the last topographic survey (1990) (Nolte 1991) for the Burned Forest, ROW and Trench treatments. Subsidence in cm.

Comparison within treatments:

Maximum subsidence took place along ROW 2, although ROW 3 has subsided only 0.84 cm less than the former (Table 4-7). ROW 1 subsided 23 cm since the last survey.

Within the trench, maximum subsidence occurred along trench 2, followed by trenches 3 and 1. Trench 2 subsided 29% and 46% more than trenches 3 and 1 respectively (Table 4-7). The total subsidence along ROW 2 was the highest subsidence rate of all SEEDS treatments.

Subsidence in the burned forest varied between 20 (Burn 1-2) and 28 cm (Burn 2-3) (Table 4-6). These subsidence rates are comparable to the lowest rates observed along the trench and ROW.

Treatment	n size	Mean	Standard Deviation
Burned Forest West	116	24.38	10.63
Burned Forest East	97	23.3	12.4
Burned Forest ROW 1-2	115	19.87	13.7
Burned Forest ROW 2-3	101	27.67	9.4
ROW 1	76	23.31	10.45
ROW 2	83	36.69	7.75
ROW 3	80	35.85	9.63
Trench 1	34	24.19	11.32
Trench 2	39	44.51	12.6
Trench 3	32	31.57	15.24

Table 4-6: Mean surface subsidence since the last topographic survey (1990) (Nolte 1991) within each treatment type at the SEEDS site. Subsidence in cm.

Total surface subsidence since clearing (1986):

The exact location of the survey points used in 1990 could not be found after the fire. It was therefore impossible to assess the subsidence of the ground where readings had previously been taken. The total surface subsidence since clearing (1986) was calculated by measuring surface elevation using the SEEDS benchmark and adding the mean total subsidence in each treatment as measured in 1990 (Nolte 1991). The amount of subsidence since 1990 was measured by using the benchmark and subtracting the 1990 mean total subsidence values in each treatment.

Mean total subsidence since clearing was greatest along the trenches, followed by the ROW and Burned Forest treatments. In 1997, total subsidence in the trench was 29% and 68% greater than the ROW and Burned Forest respectively (Table 4-7, Figure 4-3).

Treatment	n size	Mean	Standard deviation
Burned Forest	472	27.98	11.24
ROW	239	63.42	18.71
Trench	105	89.38	16.31

Table 4-7: Mean total surface subsidence since the 1986 clearing of the Burned Forest, ROW and Trench treatments at the SEEDS site (Nolte 1991). Subsidence in cm.

Ground penetrating radar:

The profiles and profile sections are presented with vertical axes showing two-way travel time and reflector depth. On all profiles, the uppermost return represented the direct air wave with a constant velocity of 0.3 m ns^{-1}. The second, and sometimes discontinuous return was the direct ground wave. This return time was dependent on the propagation velocity of the upper soil layer. Subsequent reflectors varied in each treatment and will be discussed separately. Soil moisture cores and hand probing along the survey line were used to corroborate the GPR interpretations of subsurface stratigraphy.

Burned forest surveys:

Profiles from the burned forest were expected to show the most complete stratigraphy, as this treatment was the least disturbed.

Three distinct reflectors were noted in the burned forest. Additionally, the ground wave signal was the most sporadic at these sites. On the profiles, an intermittent ground wave was present (Figure 4-4). These "skips" corresponded to the location of dry hummock tops. In the intervening, water-logged depressions, the ground wave signal was continuous.

Between 2.5 m and 3 m depth, the strongest and most continuous reflector was present. It could be followed uninterrupted for distances of 40-80 m. This reflector was generally conformable with surface topography. Dry high points on the surface corresponded to rises in the profile towards the surface (Figure 4-4).Below 5-5.5 m depth, radar signals became incoherent and were strongly attenuated. These residuals were hard to distinguish on the profiles.

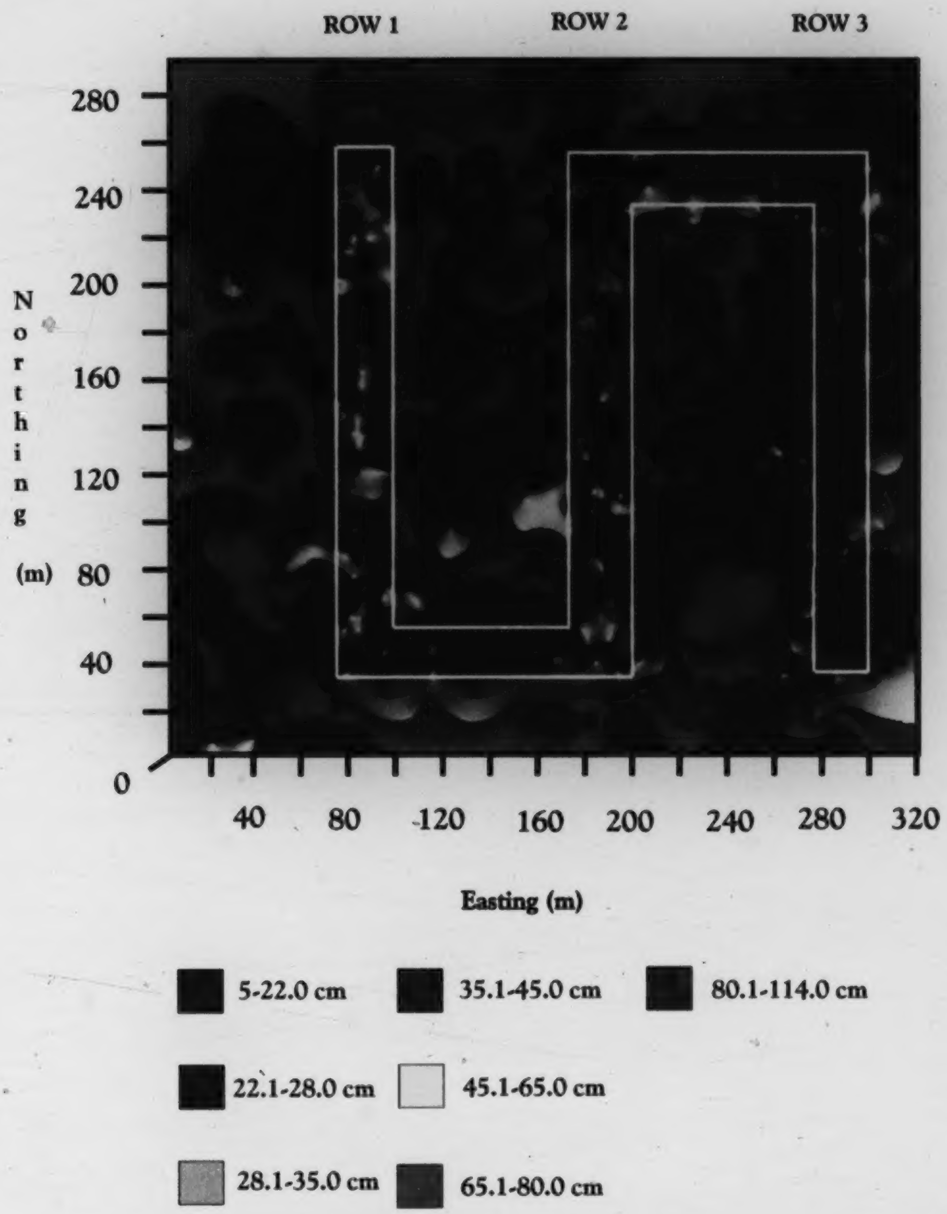

Figure 4-3: Colour-classed, hill shaded digital elevation model of total surface subsidence since clearing (1986) at SEEDS.

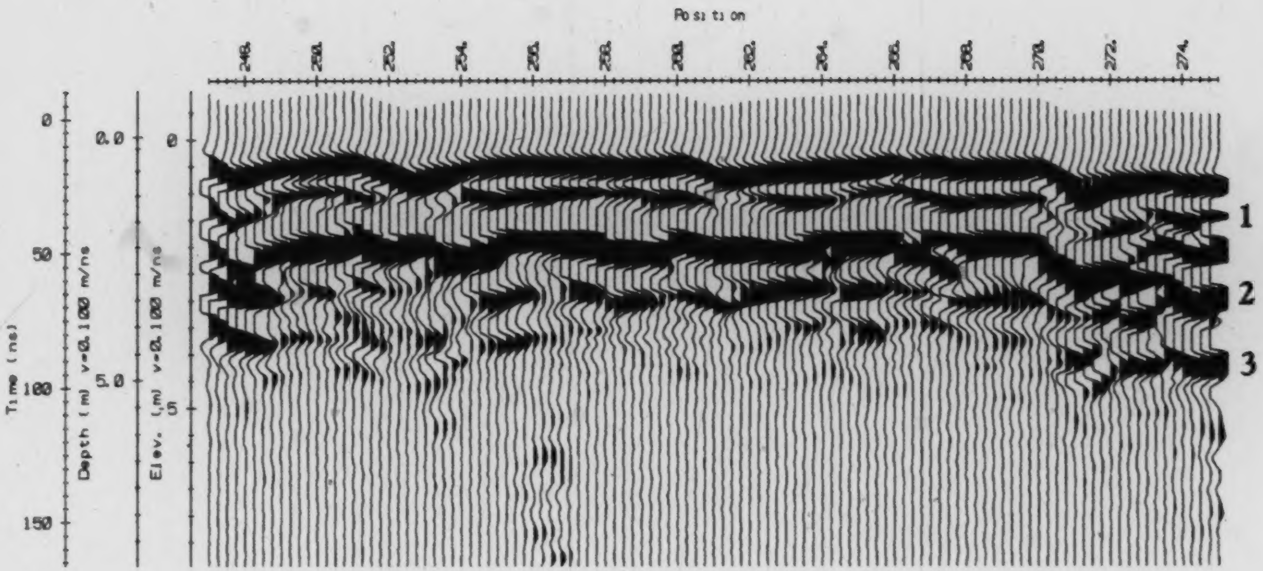

Figure 4-4: Radar profile from the Burned Forest treatment. Note the discontinuous ground-wave reflection resulting from dry hummock tops (1), the low fluctuations in the depth of the 2nd reflector (2-2.5 m depth) and, the weak signal from the 3rd reflector (~3.5m depth).

ROW surveys:

The number of reflections on the ROW profiles varied from 2 to 3. Along transect 2 (Figure 4-5), two distinct reflectors were noted, along with a weaker signal at a depth of ~3-3.5 m. Discontinuous groundwave reflectors were very strong, appearing as thick traces. The second reflector at a depth of ~2m appeared prominently on the profiles. Its depth rarely varied by more than 25-30 cm.

Signals from the third reflector were much weaker than the reflectors above. Reflections were visible at depths of 3.5-4 m and appeared in much shorter segments than on other profiles (Figure 4-5). In certain areas, the signal disappeared entirely over distances of 10-15 m (see traces 255-262.5 on Figure 4-5 a) or was extremely weak (see traces 18-32 on Figure 4-5 b).

Trench surveys:

The trench profiles were characterized by faint and sporadic reflections at depth. The initial groundwave signal was only visible in short segments. At depth, where the 2nd and 3rd reflectors were visible in the other treatments, the trench profiles had weak to non-existent signals. This was particularly striking for the 3rd reflector on certain sections (Figure 4-6). Additionally, both reflectors sometimes had a tendency to dip downward in similar fashion (Figure 4-7).

Seismic Line and Footpaths:

Other radar signals were obtained across the seismic line adjacent to the SEEDS site and on foothpaths on site. These sites had radar returns similar to the trenches and some portions of the ROW. Profiles across the seismic line (Figure 4-8) had sporadic groundwave returns and a strong signal from the lower reflectors. Signals from the third reflector were faint and sometimes absent. Footpaths and other areas of water accumulation also exhibited weak signals from the third reflector. Signal attenuation was not as pronounced as on the seismic line.

Discussion:

Surface subsidence

Seasonal subsidence:

The greatest seasonal subsidence was recorded in the trenches followed by the ROW and the burned forest. This situation was similar to pre-fire conditions where maximal subsidence was also recorded along trenches and ROWs (Nolte 1991). The principal difference in 1997 was the amount of subsidence which was twice that of 1990 values in most treatments.

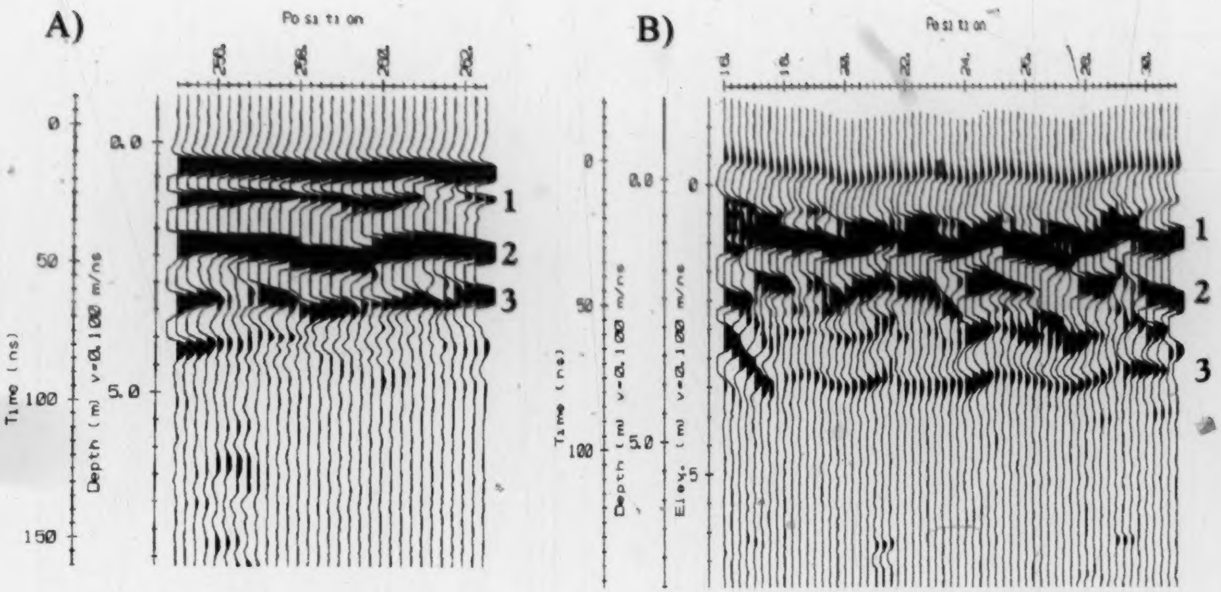

Figure 4-5: Radar profiles from the ROW treatment. **A)** (1) Ground surface with dry peat (2) active layer, (3) gravel lens. Note signal disappearance from lower reflector (traces 255-262.5). **B)** (1) Ground surface with wet peat, (2) active layer, (3) gravel lens. Note weak signal from lower reflector (traces 16-35).

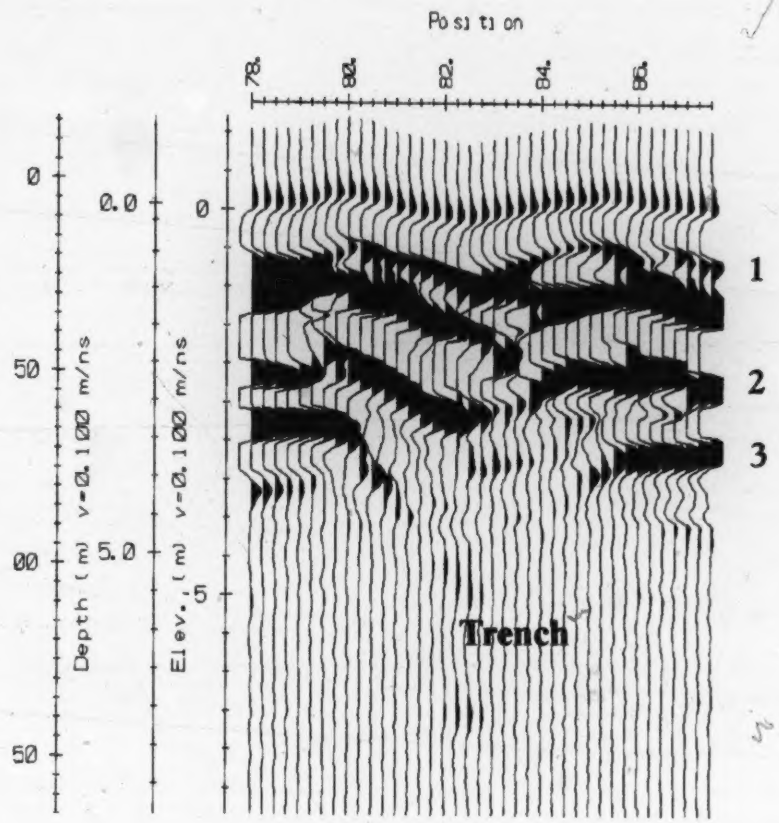

Figure 4-6: Radar profile from the Trench treatment. Note the down-dipping 2nd and 3rd reflectors and the chaotic return below 3.5m.

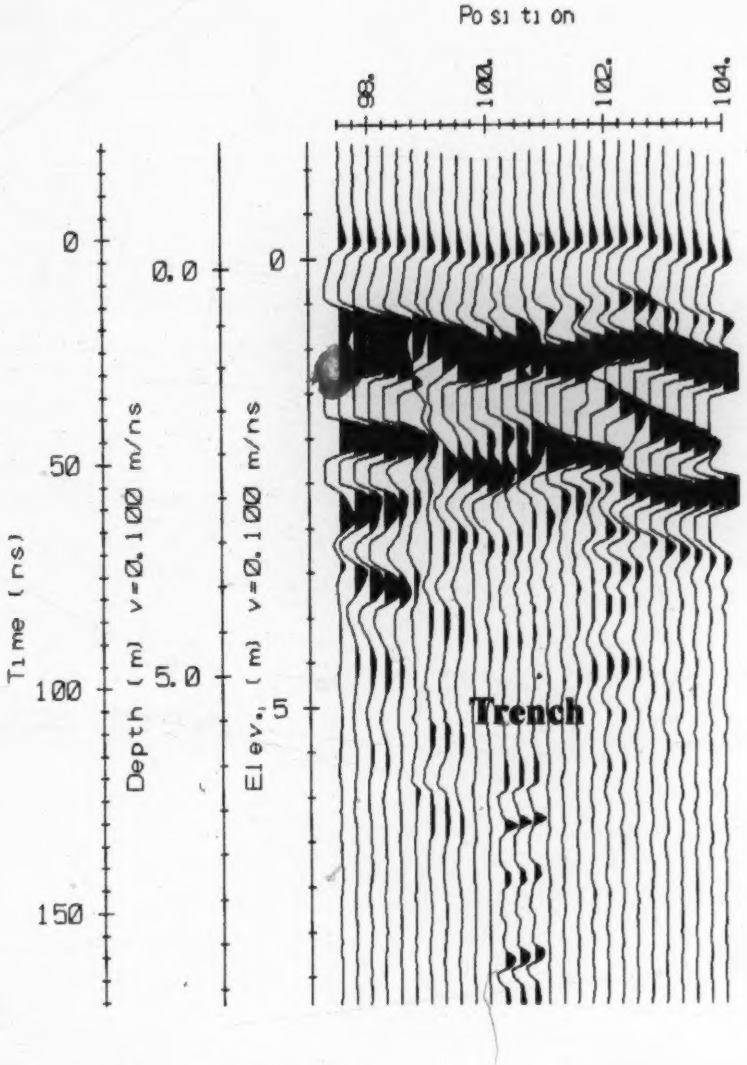

Figure 4-7: Radar profile from the Trench treatment Note Possible subsidence of the ground below ~2.5m as well as the absence of 3rd reflector in the middle of the trench.

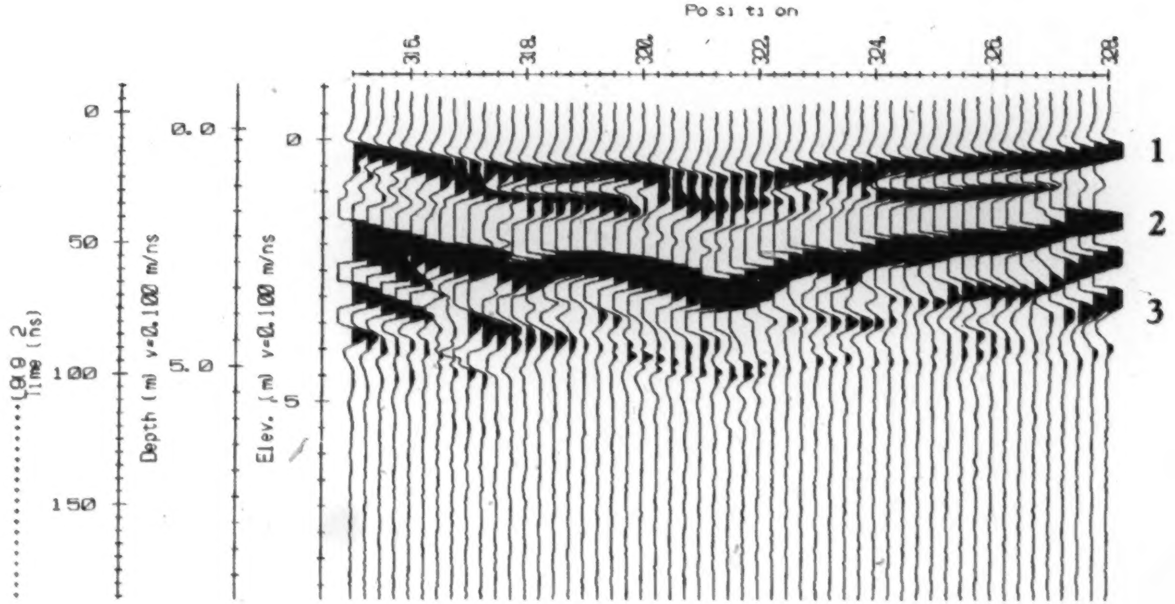

Figure 4-8: Radar profile across seismic line (traces 319-325) located west of the SEEDS site. Note the sporadic return of the ground wave (1), the strong signal from second reflector (presumed to be a gravel lens) (2) and, the faint returns from the lower reflector (3).

This sharp increase in subsidence was a direct result of the fire disturbance of 1995. The greatest change occurred in the burned forest treatment which increased by 205% over 1990 values. This was not an unexpected result since this treatment was undisturbed in 1990. The fire disturbance had its maximal effect in this treatment as the surface energy balance was disrupted and invariably led to increases in thaw depth and seasonal subsidence. It is not possible to assess how much subsidence took place between 1990 and 1995 but, assuming it was nil, the doubling of surface subsidence in three post-fire thaw seasons, is similar to results reported by Hegginbottom (1971) and Mackay (1971, 1995) who reported rapid initial increases in thaw depth and surface lowering after disturbance.

Additionally, the wildfire had an important effect on pre-disturbed treatments. Subsidence in the trench increased by 180% over 1990 values, despite the pre-existing disturbance affecting this treatment. The likely explanation for the increase in trench subsidence is increased input of meltwater from the surrounding ROW and burned forest. This would increase heat conduction into the soil as water accumulated in the trenches (Kerfoot 1973). Along the ROW, post-fire seasonal subsidence was also greater than in 1990 (+176%). This increase was to be expected as most of the ROW was disturbed to a lesser degree than the trench. The burning of the surface organics apparently produced sufficient microclimatic modifications to significantly increase thaw depth.

Within the ROW and trench treatments, the variations in seasonal subsidence were similar to those observed in 1990 (Nolte 1991). ROW 1 and its associated trench had the least subsidence. This may be partially due to the age of the disturbance (ROW 1 was cleared a year after ROWs 2-3) and to the shorter trench on this ROW. In 1990, maximum subsidence was along ROW 3 and the south link. This was attributed to increased disturbances by 1800 passes of an all-terrain cycle. The observed 1997 subsidence values may be a residual effect of this disturbance.

Total subsidence:

The similar values of total subsidence between ROW and trench treatments suggest that both treatments are exhibiting similar responses to different levels of disturbance. The initial trenching was more disruptive to the permafrost than the clearing of trees on the ROW. This difference was visible early on in the SEEDS project, as trenches exhibited greater thaw and subsidence than ROWs (Gallinger 1990, Nolte 1991, Seburn 1993). In 1997, this difference abated as similar subsidence levels were recorded at both treatments. It is possible that the wildfire disturbance has been more damaging to the ROW than the trench. In effect, the ROW may have "caught-up" to the trench disturbance level. The same mechanism may partially explain the variations within the treatments. Trench 2 and ROW 2 had the most subsidence, followed by ROW 3 and the associated trench.

Also, ROW 3 was reported to have been more severely disturbed during construction (Nolte 1991). The initial disturbance on ROW 3 may have been sufficient to supersede any of the fire effects, explaining why little less subsidence has occurred. The higher rates of subsidence on ROW 2 may reflect a stronger localised response to the fire. This response may be greater than on ROW 3, resulting in the highest subsidence rates.

Ground penetrating radar profiles:

Burned forest treatment:

The discontinuous reflections within the ground wave are the result of a dielectric contrast between the dry organic mat and the wetter underlying mineral horizon. The lateral extent of the reflections resulted from areas of large hummocks, elevated 15-20 cm above the ground. The strong degree of association between microtopographic high points and these signals confirms this relationship. In the surrounding depressions, ponded water or saturated organics were often observed during the survey. Standing water also implied saturation of the underlying mineral horizon. The relative homogeneity in moisture contents between organic/mineral horizons would not allow for the GPR signal to differentiate between the mediums, so that it appeared as a continuous reflector on the profiles. On the dryer high points, the dielectric contrast would be sufficient to generate an, albeit, weak signal. In past studies, GPR has proven successful in delimiting the interface between peat and underlying mineral sediment, due to the differences in electrical properties between the two media (Horvath 1998). Radar signals were strongest when the contrast in dielectric permittivity across an interface was large. In turn, dielectric permittivity is primarily controlled by moisture content (Davis *et al.* 1977, Wong *et al.* 1976). Theoretically, variations in moisture content as low as one to three percent by weight can be detected by GPR (Hanninen 1992a, Theimer *et al.* 1994). From soil moisture cores (Chapter 3), the difference in gravimetric moisture content between surface organics and mineral soil varied between 7-12%, making the interface detectable.

The second reflector was from a gravel layer present throughout the site. This gravel was noted by Kershaw and Evans (1987) during coring at the site in 1986. It was also observed in some of the cores extracted in 1997 (Appendix A) and may have prevented further coring in many instances. From soil cores, this layer ranged in thickness from ~5-12 cm and GPR profiles indicated it occurred in long continuous layers as well as small isolated lenses. In some instances, both the gravel lens and the 3rd reflector (permafrost table) merged and appeared as a single, large reflector. This only occurred in the burned forest where thaw depth had not yet progressed beyond the depth of the gravel lens and the permafrost table was in the vicinity of this sedimentary unit. The abrupt change in grain size, and therefore dielectric characteristics, from the surrounding silts accounted for the prominence of this unit on the profiles (Barry and Pollard 1992, Seguin *et al.* 1989, Smith and Jol 1992).

The deepest reflector on the profiles possibly represented an old active layer created under cooler climatic conditions (possibly during the Hypsithermal) or as a result of previous disturbances that occurred as much as 300 years ago. The depths noted on the profiles corresponded approximately to the stratigraphic sequence derived from the soil cores where ice-cemented layers were attained at depths between 1.2-1.6 m (Chapter 2). Additionally, active layer thickness as measured by hand probing to refusal along the radar line corroborated the depths interpreted from the profiles. The Rank Correlation Coefficient, R, between hand probing and radar depth was 0.768. Although not perfect, the correlation was still good and may have stemmed from observational errors on the radar profiles as well as during field measurements. As noted by Doolittle *et al.* (1990) the probing depths may be the largest sources of error as slight spatial discrepancies between the probe site and the radar track may have acted to lower correlation. Variations in the combined thickness of the organic mat and the active layer as great as 15 cm within a 30 cm radius of an observation site were observed. With such variations over small distances, it is unlikely that any method of measurement could produce identical results. The coarseness of the vertical axis and the width of the radar trace may have also been potential sources of errors when readings were taken. The undulating and conformable nature of the reflector in relation to the surface was further evidence for it being the top of the permafrost table. Brown (1967) reported that the surface of the frozen layer varies with the microtopography of the soil surface.

ROW surveys.

The strong groundwave returns suggested thicker and dryer organic accumulations at the surface. It was therefore possible that drainage was better or that pre-fire organic thickness was greater in these areas. Organic mat thickness may also reflect burn severity at these sites, with greater accumulations remaining in the less severely burned areas. The constant depth of the second reflector and its similar appearance on the profiles indicated this was the gravel lens observed on the burned forest profiles. The generally faint signal received from the third reflector was indicative of the degree of disturbance on the ROWs. Assuming this reflector was the bottom of the active layer, the faint signal suggested that ice content at this interface had decreased, resulting in a weaker return of the radar signal. Also, GPR profiles indicated an increase in the thaw depth beyond the values recorded by hand-probing (Chapter 3). In 1997, mean thaw depth along the ROWs was 136.4 cm (Chapter 3), a depth which corresponded approximately to the depth of the second reflector (gravel lens). Since the probing method used probe refusal as an indication of the maximum thaw depth, it was possible that hand-probing grossly underestimated thaw depth. Many times during probing, the probe could not be pushed further than 200-230 cm depth because of the confining pressures from the surrounding thawed soil. Similarly, the probe was extremely hard to extract when it was pushed beyond ~2.5 m depth.

Trench surveys:

The weak signal return from the first trench reflector resulted from high moisture contents and saturation of the sparse organic cover. Throughout the SEEDS site, the trench constituted a shallow depression 20-30 cm lower than the surrounding ROW. This created preferential drainage towards the trench, keeping the moisture content high. Additionally, during construction of the SEEDS site, surface organics were removed with excavation and mixed-in during backfilling (Kershaw 1986). Although some organic material has grown back since the fire, the organic mat found elsewhere at SEEDS was generally absent from the trench. These conditions explained the lack of sporadic groundwave signals that were observed in the burned forest and ROW treatments.

Subsequent faint signals from the deeper reflectors result from the high degree of disturbance during site construction. The trenching and back-filling disturbed and truncated sediment layers to a depth of 50 cm. Additionally, trenches exhibited the deepest thaw depths and these thick thawed sediments attenuated radar signals resulting in faint returns.

Between traces 81.5 and 83.5 (Figure 4-6), the third reflector was discontinuous and dipped downward. The two reflectors above it were also truncated and displaced. These signals were the result of surface subsidence that may have modified the position of the gravel lens following the localized deepening of the active layer. Along the other transect, radar signals were suggestive of significant deepening of the active layer (Figure 4-7). On these profiles, the water-saturated silts strongly attenuated signal penetration, resulting in chaotic traces that did not penetrate below 2.5-3 m. This type of signal return has been recognized as typical of a thawed, fine-grained active layer (Seguin *et al.* 1989, Pilon *et al.*1992, Doolittle *et al.* 1990).

Seismic line and footpaths surveys::

The signals from the third reflector along the seismic line were faint and sometimes absent, suggesting an overdeepened active layer over these areas. Foothpaths and other areas of water accumulation also had weak signals from the third reflector. Signal attenuation was however not as strong as on the seismic line. The main effect of ponded water on signal returns seemed to be a complete attenuation of the groundwave, followed by chaotic returns down the trace. Subsidence did not seem as deep as in the trench since internal stratigraphy was not disturbed.. This was not unexpected when considering the difference in the degree of disturbance of these two sites. Most changes created by ponded water stemmed from its higher heat capacity which increased soil temperatures (Kerfoot 1973). In contrast, the trench and seismic lines were heavily disturbed , with surface organics being severely trampled and/or completely removed, thereby modifying the energy balance at the surface.

Interestingly, the comparison of radar profiles between the trenches and the seismic line can possibly give information on the recovery time of such disturbances. It was apparent that even 25 years after initial disturbance, the permafrost beneath the seismic line had not recovered to its pre-disturbance conditions. The depth of the active layer had increased and it did not seem to be aggrading, as illustrated by the absence of an ice-rich layer at the freezing front. This further suggested that permafrost below the trench could still be degrading for at least 10 years, despite ongoing plant recovery (assuming constant climatic conditions).

Conclusion:

Three thaw seasons after fire, there were significant differences in the mean seasonal subsidence of all SEEDS treatments. Mean subsidence was highest in the trench and the ROW treatments. The burned forest had only subsided 2 cm and 6 cm less than the ROW and trench respectively. This situation was similar to pre-fire conditions where maximum subsidence occurred in the trench, ROW and burned forest. In 1997, the principal difference was the amount of subsidence which was double the pre-fire values for most treatments. This increase was a direct result of the surface disturbance by fire. The burned forest had the strongest response to the wildfire as the increase in thaw depth was 205% greater than the 1990 pre-fire values. The rapid initial response of this treatment was due to the fact that the burned forest was undisturbed (unlike the ROW and trench) before the fire. Additionally, the wildfire had an important impact on pre-disturbed treatments as both ROW and trench exhibited significant increases in subsidence.

Total subsidence since clearing was highest in the trench and ROW. The burned forest had the smallest change. This was due to two factors: the time since disturbance and the severity of the disturbance. The trench was the most disturbed treatment and it had the greatest surface subsidence. Inversely, the burned forest was moderately disturbed by wildfire and had the least subsidence.

Ground penetrating radar proved to be useful for active layer investigations. At least 3 reflectors were visible on radar profiles from the burned forest. In the other two treatments, 2-3 reflectors were visible but the quality of their signal was variable. Signal attenuation was strongest in the most disturbed treatments (trench and ROW) where a thick active layer decreased signal penetration. The interfaces between thawed and frozen material were strong continuous reflectors. These signals permitted the detection of layers of coarse mineral material. Finally, because of the high dielectric contrast between thawed and frozen material, the bottom of the active layer was visible as a strong continuous reflector. The active layer depths inferred from the GPR profiles sometimes exceeded values obtained by hand-probing. This was particularly true in areas where thawed sediments could not be entirely penetrated. This implies that hand-probing may have underestimated maximum thaw depth, particularly after 1991-1992 when the deeper thaw depths made probing more difficult.

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Chapter 5: Conclusions

Wildfires modify permafrost-affected soils by changing the energy balance at the ground surface (Brown 1983). This usually leads to an increase in soil temperatures and the melting of ground ice, resulting in a thickening of the active-layer. Geomorphic repercussions of ground-ice melting include surface subsidence because of the volume loss associated with this phase change. Additionally, the drainage of meltwater leads to secondary subsidence as pore space decreases.

This thesis has examined the microclimatic and geomorphic responses of a Subarctic upland forest underlain by permafrost, in the third thaw seasons following wildfire.

Microclimatic responses to wildfire:

The burning of the *SEEDS* site has lead to substantial modifications in the energy budget of the surface. The burned treatments received levels of short-wave radiation that were 21-50% greater than the control treatment. Outgoing short-wave radiation was lower in the burned treatments by 14-30%. This resulted from the sudden darkening of the organic layer following burning. The darker surface led to a decrease in surface albedo. This, in turn, favored greater absorption of solar radiation and increased soil temperatures in the burned treatments.

Incoming long-wave radiation was also greater in the burned treatments than in the control. This occurred as a result of tree canopy removal which allowed the penetration of 40-79% more radiation. The warmer soil temperatures in the burned treatments led to higher amounts of outgoing long-wave radiation over these surfaces.

The removal of the vegetation canopy also led to a decrease in relative humidity and an increase in wind speeds over the burned treatments. Air temperatures at 150 cm height were cooler in the burned treatments because of greater heat advection.

Burning also altered snowpack characteristics. The SEEDS treatments had thinner and denser snowpacks than during pre-fire conditions. This was again due to vegetation removal which favored snow redistribution and wind action. A *Heat Transfer Coefficient* (*HTC*) (Kershaw 1991) was calculated to assess the potential for heat loss from the soil. High *HTC* values were found in the burned forest and on some ROW sites, suggesting that these sites would be poorly insulated and would allow greater frost penetration.

Soil moisture and active layer depth modifications following wildfire.

Burning led to a decrease in soil moisture content as a result of ground-ice melting and meltwater drainage. The greatest decrease occurred in the upper 15-20cm of the soil column as the surface organic layer was drier and thinner than in the control treatment. The lower post-fire albedo of the organic layer and the increase in surface temperatures favored greater rates of evaporation and, hence drier conditions. Below 20cm, moisture content was again lower than in pre-fire conditions. However, the differences between treatments were more variable and this was thought to be a function of the age and severity of the disturbance. The trench, the most severely disturbed treatment, had low moisture contents at depths greater than all other treatments. This likely resulted from the time since ground-ice thawing had begun, allowing for large amounts of meltwater to drain away. The ROW also had lowered moisture contents, although not as deeply as the trench. Finally, the burned forest had the least amount of change in soil moisture content, presumably since this was the least disturbed treatment and the time since disturbance is still short.

The active layer response to the wildfire was variable throughout the SEEDS treatments. The trench treatment had the least amount of post-fire active layer increase, followed by the ROW and the burned forest treatments. The trench sites were little affected by the wildfire as thaw depths were not significantly different from the last pre-fire measurements and the 1996 values (Nolte 1991, Nolte and Kershaw 1998, Seburn 1993, Seburn and Kershaw 1997). The majority of the increase in active layer depths in the ROW and trench treatments were a result of the initial disturbance and likely occurred between 1986 and 1995. This low increase likely stemmed from the degree of disturbance of the initial clearing of the ROW's, that superseded the microclimatic modifications caused by wildfire. The burned forest sites exhibited significant increases in thaw depths. This was a result of the modification of the surface energy balance resulting from the burning of the organic mat and the removal of the tree canopy, allowing thaw to progress deeper into the ground.

Thermokarst and surface subsidence following wildfire:

Post-fire seasonal subsidence was highest in the trench, followed by the ROW and burned forest. This pattern was similar to pre-fire conditions (Nolte 1991). The principal difference was the amount of seasonal subsidence which was almost doubled in 1997 compared to the pre-fire values. This increase was a direct result of the surface disturbance inflicted by the wildfire. The burned forest had the strongest response to the wildfire as the increase in thaw depth was 205% greater than the 1990 pre-fire values (Nolte 1991). The rapid initial response of this treatment was due to the fact that the burned forest was undisturbed (unlike the ROW and trench) before the fire. Additionally, the wildfire had an important impact on pre-disturbed treatments as both ROW and trench had significant increases in thaw depth.

Total subsidence since clearing was highest in the trench and ROW. The burned forest had the smallest increase. This was again due to the time since disturbance and the severity of the disturbance. The trench was the most disturbed treatment and it had the largest increase in total surface subsidence since clearing. Inversely, the burned forest was moderately disturbed by wildfire and it had the least subsidence.

Ground penetrating radar proved to be a very useful tool for active layer investigations. At least 3 reflectors were visible on radar profiles from the burned forest. In the other two treatments, 2-3 reflectors were visible but the quality of their signal was variable. Signal attenuation was strongest in the most disturbed treatments (trench and ROW) where a thick active layer decreased signal penetration. The interfaces between thawed and frozen material produced strong continuous reflectors. These signals permitted the detection of layers of coarse mineral material. Finally, because of the high dielectric contrast between thawed and frozen material, the bottom of the active layer was visible as a strong continuous reflector. The active layer depths inferred from the GPR profiles sometimes exceeded values obtained by hand-probing. This was particularly true in areas where thawed sediments prevented the penetration of the probe. This implies that hand-probing may have underestimated maximum thaw depth, particularly after 1991-1992 when the deeper thaw depths made probing more difficult.

Three thaw seasons after fire, there were significant differences in the mean seasonal subsidence of all SEEDS treatments. Mean subsidence was highest in the trench and the ROW treatments. The burned forest only subsided 1.7 cm and 6.2 cm less than the ROW and trench respectively. This situation was similar to pre-fire conditions where maximum subsidence occurred in the trench, ROW and burned forest. In 1997, the principal difference was the amount of subsidence which was double the pre-fire values for most treatments. This increase was a direct result of the surface disturbance caused by the wildfire. The burned forest was most altered by the wildfire as the increase in thaw depth was 205% greater than the 1990 pre-fire values. The rapid initial response of this treatment was due to the fact that the burned forest was undisturbed (unlike the ROW and trench) before the fire. Additionally, the wildfire had an important impact on pre-disturbed treatments as both ROW and trench had significant increases in thaw depth.

Total subsidence since clearing was highest in the trench and ROW. The burned forest had the smallest increase . This was due to two factors: the time since disturbance and the severity of the disturbance. The trench was the most disturbed treatment and it had the largest increase in surface subsidence. Inversely, the burned forest was moderately disturbed by wildfire and it had the least subsidence.

Future avenues of research:

This study was an examination of the microclimate and geomorphic responses of a subarctic upland forest, three thaw seasons after wildfire. Although this study is over, the results reported herein are limited by the short time span over which it was conducted. The microclimate and geomorphic changes observed in 1997 continue to respond to the initial disturbance and will so for the forseable future. Therefore, the results of this study provide a basis for comparison for future work on the site. The SEEDS site is unique in that it allows a very detailed analysis of micro- and meso-scale processes occurring over a small geographical area. These conditions will allow monitoring of the long-term post-fire response of discontinuous permafrost in a detail of spatial and temporal scales that has never been reported. In this light, I have listed possible avenues of further research:

- Throughout this thesis, the transfer of heat into the soil was invoked many times to explain increases in active layer depth and surface subsidence. Unfortunately, the importance of this parameter remained purely speculation as no data were collected to support such statements. Therefore, future efforts should be made to quantify soil heat flux as well as the soil characteristics that influence thermal conductivity (namely porosity, ice/water content, bulk density).

- In the same light, a better system of soil temperature measurements should be used. The current set-up does not allow for accurate measurement of soil temperatures below 100 cm depth as thermocouples are unevenly spaced. A better system could employ a series of thermocouples, evenly spaced at 5 or 10 cm. This thermocouple string could be anchored in the permafrost as deeply as possible (possibly 3-4 m depth). Such a setup would allow for very precise temperature measurements with depth and the possibility to locate the bottom of the active layer with the 0°C isotherm. Combining these temperature measurements with better characterization of soil conditions would permit very detailed analysis of active layer development and the seasonal/annual fluctuations of the active layer. This will be increasingly important if the active layer increases beyond depths where the probing method can be used. Finally, using this setup would give information on the maximum thaw depth and the freeze-back process. Both need to be measured and quantified at SEEDS.

- Increases in surface subsidence and thaw depth should be monitored closely, especially in the burned forest as this site will respond to the wildfire disturbance over the next few years. Additionally, thaw depth and subsidence should be monitored in the ROW and trench treatments to assess the importance of the fire disturbance on the pre-disturbed treatments. It is of interest to know if these treatments continue to respond strongly to the fire disturbance or if the initial clearing disturbance is overriding the fire disturbance.

- Finally, the extensive pre- and post-fire database would be particularly well suited to the development of a computer model. Adding data on soil temperatures and moisture could allow the development of a coupled atmosphere-permafrost model. If a suitable model was developed, predictions of permafrost response could be made under various conditions. This could include climatic warming or cooling and the effects of repeated disturbances (successive wildfires occurring over a short time span).

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Appendix

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-14	13.89	5.36	61.41	**0-20**	29.60	11.08	62.56	**0-14**	22	61	17	10YR 2/1
14-20	47.89	17.52	63.41	**20-45**	107.70	54.47	49.43	**14-20**	21	60	19	10YR 3/1
20-30	67.62	31.54	53.36	**45-65**	123.50	73.00	40.89	**20-30**	20	62	18	10YR 4/3
30-40	74.29	43.45	41.51	**65-80**	118.30	70.18	40.68	**30-40**	20	64	16	10YR 3/3
40-50	83.36	55.35	33.60	**80-90**	171.40	100.91	41.13	**40-50**	19	63	18	10YR 3/3
50-60	80.94	63.17	21.95	**90-100**	189.60	112.36	40.74	**50-60**	23	57	20	10YR 4/2
60-70	89.94	61.36	31.78	**100-115**	254.30	149.72	41.12	**60-70**	25	58	17	10YR 4/3
70-80	95.08	43.36	54.40					**70-80**	14	68	18	10YR 3/3
80-90	102.41	65.75	35.80					**80-90**	17	65	18	10YR 4/3
90-102	79.66	42.58	46.55					**90-102**	17	64	19	10YR 4/3
102-110	82.11	41.99	48.87					**102-110**	15	64	21	10YR 5/2
110-120	77.11	39.71	48.50					**110-120**	19	61	20	10YR 5/2
120-131	125.18	78.66	37.16					**120-131**	22	62	16	5YR 3/4
131-140	80.87	49.95	38.24					**131-140**	28	56	16	5YR 3/4
140-150	114.57	73.97	35.44					**140-150**	26	55	19	5YR 2/4
150-160	96.99	65.64	32.32					**150-160**	27	51	22	10YR 4/2
160-171	152.04	121.72	19.94					**160-171**	29	51	20	10YR 5/4
171-180	106.32	79.60	25.13					**171-180**	27	47	26	10YR 5/3
180-187	87.63	70.56	19.48					**180-187**	27	48	25	10YR 6/3

Appendix A-1: 1997 Soil moisture characteristics and texture classification of permafrost cores from the Burned Forest treatment, SEEDS, NWT. Sample site was located in the burned forest between the seismic line and ROW 1. Samples were collected 30 May 1997 and 14 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-13	15.80	4.26	73.04	**0-25**	22.30	12.61	43.45	**0-13**	22	57	21	7.5YR 2/1
13-20	59.90	16.90	71.79	**25-40**	110.60	69.07	37.55	**13-20**	21	60	19	7.5YR 3/1
20-30	54.60	21.53	60.57	**40-60**	101.00	55.54	45.01	**20-30**	17	60	23	10YR 2/2
30-42	90.60	48.03	46.99	**60-85**	134.50	84.70	37.03	**30-42**	16	68	16	10YR 2/3
42-52	68.00	39.11	42.49	**85-100**	136.60	70.27	48.56	**42-52**	14	67	19	10YR 3/3
52-63	73.80	48.91	33.72	**100-115**	184.20	101.45	44.92	**52-63**	17	61	22	10YR 4/2
63-70	57.10	36.07	36.82	**115-122**	158.30	84.32	46.73	**63-70**	25	58	17	10YR 4/3
70-80	120.00	58.82	50.99					**70-80**	14	68	18	7.5YR 3/3
80-91	126.20	72.30	42.71					**80-91**	17	65	18	10YR 3/3
91-100	86.30	51.36	40.48					**91-100**	17	64	19	10YR 4/3
100-113	171.20	131.80	23.01					**100-113**	15	64	21	10YR 5/2
113-120	103.70	80.08	22.78					**113-120**	19	61	20	10YR 4/2
120-130	135.30	104.60	22.69					**120-130**	22	62	16	7.5YR 3/4
130-140	113.50	67.88	40.19					**130-140**	28	56	16	7.5YR 3/4
140-150	129.80	90.59	30.21					**140-150**	26	55	19	7.5YR 3/4
150-160	140.50	104.40	25.69					**150-160**	27	51	22	10YR 3/2
160-170	174.10	126.21	27.51					**160-170**	29	51	20	10YR 4/2
170-181	131.20	98.38	25.02					**170-181**	27	47	26	10YR 5/3
180-190	112.50	88.12	21.67					**180-190**	27	48	25	10YR 4/3
190-200	150.60	117.21	22.17					**190-200**	28	48	24	10YR 5/3
200-212	193.40	148.88	23.02					**200-212**	26	45	29	10YR 5/4
212-220	126.20	100.95	20.01					**212-220**	27	50	23	10 YR 5/4

Appendix A-2: 1997 Soil moisture characteristics and texture classification of permafrost cores from the Burned Forest treatment, SEEDS, NWT. Sample site was located in the burned forest between ROW 2 and ROW 3. Samples were collected 28 May 1997 and 14 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	**Wet Weight (g)**	**Dry Weight (g)**	**% Moisture Content**	**Depth (cm)**	**Wet Weight (g)**	**Dry Weight (g)**	**% Moisture Content**	**Depth (cm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Colour**
0-10	8.30	1.77	78.67	**0-25**	12.40	3.60	70.94	**0-10**	22	57	21	10YR 1.7/1
10-20	52.70	14.25	72.96	**25-40**	79.30	32.74	58.71	**10-20**	21	60	19	10YR 3/1
20-30	89.80	28.18	68.62	**40-55**	119.30	65.64	44.98	**20-30**	17	60	23	10YR 2/1
30-41	60.49	23.17	61.70	**55-75**	157.90	86.62	45.14	**30-41**	16	68	16	10YR 3/3
41-49.5	84.33	55.67	33.98	**75-85**	180.20	103.16	42.75	**41-49.5**	14	67	19	10YR 3/3
49.5-60	69.81	55.76	20.12	**85-95**	283.90	176.77	37.74	**49.5-60**	17	61	22	10YR 3/2
60-70	114.30	82.55	27.78	**95-110**	159.50	91.29	42.76	**60-70**	25	58	17	10YR 2/2
70-81	110.59	60.00	45.75					**70-81**	14	68	18	10YR 3/3
81-90	80.30	39.90	50.32					**81-90**	17	65	18	10YR 4/3
90-101.5	124.30	73.65	40.75					**90-101.5**	17	64	19	10YR 3/4
101.5-110	89.40	59.35	33.61					**101.5-110**	15	64	21	7.5YR 3/2
110-120	73.73	34.98	52.55					**110-120**	19	61	20	7.5YR 3/3
120-129.5	102.50	59.33	42.11					**120-129.5**	22	62	16	5YR 4/1
129.5-140	151.77	94.63	37.65					**129.5-140**	28	56	16	5YR 4/2
140-150	112.10	66.55	40.63					**140-150**	26	55	19	5YR 2/4
150-160	121.35	89.96	25.87					**150-160**	27	51	22	7.5YR 4/1
160-171	131.56	101.97	22.49					**160-171**	29	51	20	7.5YR 4/2
171-180	114.95	91.38	20.50					**171-180**	27	47	26	10YR 4/2
180-191	161.78	128.90	20.32					**180-191**	27	48	25	10YR 5/2
191-200	158.82	132.80	16.38					**191-200**	28	48	24	10YR 4/3
200-204	66.58	54.02	18.86					**200-204**	26	45	29	10YR 3/3

Appendix A-3: 1997 Soil moisture characteristics and texture classification of permafrost cores from the Burned Forest treatment, SEEDS, NWT. Sample site was located in the burned forest between ROW 1 and ROW 2. Samples were collected 28 May 1997 and 14 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-10	24.28	7.05	70.96	**0-20**	18.20	6.67	63.37	**0-10**	27	54	19	7.5YR 2/1
10-20	42.19	13.45	68.12	**20-50**	88.40	55.05	37.73	**10-20**	25	57	18	10YR 2/1
20-30	133.76	63.00	52.90	**50-60**	57.50	32.42	43.62	**20-30**	23	57	20	7.5YR 3/2
30-40	110.34	62.36	43.48	**60-70**	156.30	92.65	40.72	**30-40**	26	50	24	7.5YR 3/3
40-50	63.58	32.76	48.47	**70-80**	117.70	69.29	41.13	**40-50**	21	52	27	7.5YR 4/2
50-60	78.89	47.76	39.46	**80-90**	125.70	72.29	42.49	**50-60**	26	55	19	10YR 3/2
60-70	127.30	90.24	29.11	**90-97**	126.50	74.64	41.00	**60-70**	19	62	19	10YR 3/3
70-80	116.14	92.91	20.00					**70-80**	14	68	18	10YR 4/2
80-90	94.87	78.42	17.34					**80-90**	22	61	17	10YR 4/1
90-96	93.68	73.01	22.06					**90-96**	24	57	19	10YR 4/1

Appendix A-4: 1997 Soil moisture characteristics and texture classification of permafrost cores from the Burned Forest treatment, SEEDS, NWT. Sample site was located in the burned forest 7 m east of ROW 3. Samples were collected 26 May 1997 and 11 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-13	12.80	3.65	71.48	**0-20**	16.30	3.68	77.45	**0-13**	14	64	22	10YR 3/2
13-20	44.10	14.19	67.83	**20-45**	32.60	7.86	75.88	**13-20**	12	65	23	10YR 3/3
20-25	41.00	13.09	68.07	**45-55**	56.70	21.99	61.21	**20-25**	16	63	21	10YR 3/2
25-29	26.20	8.83	66.30	**55-75**	75.90	39.38	48.11	**25-29**	22	58	20	10YR 2/3
29-32	19.00	7.25	61.84	**75-90**	199.80	110.87	44.51	**29-32**	19	57	24	7.5YR 3/3
32-36	17.50	8.32	52.46	**90-100**	349.30	228.38	34.62	**32-36**	17	63	20	10YR 4/2
36-38	16.80	5.60	66.67	**100-110**	286.80	186.11	35.11	**36-38**	24	58	18	10YR 4/3
38-50	113.00	51.17	54.71	**110-120**	307.80	202.63	34.17	**38-50**	21	56	23	10YR 4/2
50-60	90.80	53.54	41.04	**120-128**	256.40	159.95	37.62	**50-60**	23	57	20	10YR 5/2
60-70	109.90	58.51	46.76					**60-70**	20	59	21	10YR 5/2
70-80	78.40	49.54	36.81					**70-80**	18	60	22	2.5Y 5/2
80-89	99.40	65.63	33.97					**80-89**	26	51	23	2.5Y 5/1
89-100	163.20	129.14	20.87					**89-100**	31	47	22	2.5Y 5/3
100-110	63.20	48.61	23.08					**100-110**	25	52	23	10YR 6/2
110-120	146.30	103.72	29.10					**110-120**	24	57	19	10YR 5/1
120-130	133.30	81.87	38.58					**120-130**	23	55	22	10YR 5/2
130-140	161.40	113.79	29.50					**130-140**	31	50	19	10YR 6/2
140-150	92.60	60.01	35.19					**140-150**	30	48	22	10YR 6/2
150-160	112.90	83.05	26.44					**150-160**	32	42	26	10YR 5/2
160-170	135.00	99.03	26.64					**160-170**	30	51	19	10YR 5/2
170-180	126.40	94.80	25.00					**170-180**	28	51	21	10YR 5/2

Appendix A-5: 1997 Soil moisture characteristics and texture classification of permafrost cores from the ROW treatment, SEEDS, NWT. Sample site was located on ROW 1 (next to cover plot #40). Samples were collected 27 May 1997 and 14 August 1997.

	SPRING				LATE SUMMER		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-15	11.57	6.55	43.36	**0-25**	27.40	9.34	65.91
15-26	106.80	42.57	60.14	**25-35**	67.60	42.64	36.92
26-35	65.00	25.50	60.77	**35-55**	141.60	105.58	25.44
35-46	107.40	60.24	43.90	**55-75**	120.70	89.40	25.93
46-55	78.80	43.08	45.33	**75-90**	123.70	94.58	23.54
55-63	85.50	48.77	42.96	**90-115**	175.60	134.91	23.17
63-70	104.60	66.16	36.75	**115-125**	165.70	129.57	21.80
70-80	142.50	100.18	29.70	**125-140**	146.30	113.48	22.43
80-90	133.00	88.62	33.37	**140-152**	134.00	103.60	22.69
90-100	104.60	69.57	33.49				
100-110	120.90	80.48	33.43				
110-130	121.20	74.73	38.34				
130-135	68.70	49.77	27.55				

Appendix A-6: 1997 Soil moisture characteristics of permafrost cores from the ROW treatment, SEEDS, NWT. Sample site was located on ROW 1 (next to cover plot #48). Samples were collected 25 May 1997 and 16 August 1997.

	SPRING		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-10	62.30	34.21	45.09
10-21	63.90	33.04	48.29
21-30	83.90	33.28	60.33
30-40	103.70	46.79	54.88
40-50	87.00	41.39	52.43
50-60	77.60	43.84	43.51
60-70	70.90	41.82	41.02
70-81	95.50	61.48	35.62
81-90	72.10	48.59	32.61
90-110	103.40	74.36	28.09
110-120	65.90	49.35	25.11
120-130	97.00	73.06	24.68
130-140	104.40	73.95	29.17
140-160	100.90	77.00	23.69
160-171	52.60	38.66	26.50
171-180	65.00	47.90	26.31
180-190	104.40	81.72	21.72
190-195	77.50	55.84	27.95

	LATE SUMMER		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-20	24.00	11.85	50.63
20-35	60.00	32.98	45.03
35-50	45.10	24.48	45.71
50-70	108.80	57.94	46.75
70-90	120.80	68.17	43.57
90-110	143.20	99.30	30.66
110-130	139.30	98.83	29.05
130-150	143.00	108.27	24.29
150-165	152.80	111.43	27.07
165-175	149.30	111.96	25.01
175-190	98.30	61.82	37.11
190-199	76.00	46.61	38.68

	TEXTURE			
Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-10	17	65	18	10YR 2/2
10-21	14	65	21	10YR 2/2
21-30	17	63	20	10YR 4/2
30-40	19	60	21	10YR 3/1
40-50	20	61	19	10YR 2/2
50-60	17	60	23	10YR 3/2
60-70	19	57	24	10YR 4/1
70-81	21	60	19	10YR 4/2
81-90	20	62	18	10YR 4/3
90-110	18	60	22	10YR 4/3
110-120	24	55	21	10YR 5/2
120-130	21	61	18	10YR 5/2
130-140	26	51	23	7.5YR 4/4
140-160	24	56	20	7.5YR 5/4
160-171	18	60	22	7.5YR 5/4
171-180	21	61	18	10YR 5/3
180-190	22	58	20	10YR 5/4
190-195	24	58	18	10YR 6/3

Appendix A-7: 1997 Soil moisture characteristics of permafrost cores from the Trench treatment, SEEDS, NWT. Sample site was located in the trench on ROW 2 (~13 m south of the microclimate station). Samples were collected 25 May 1997 and 16 August 1997.

Depth (cm)	SPRING Wet Weight (g)	 Dry Weight (g)	 % Moisture Content
0-15	18.40	9.36	49.13
15-23	48.50	23.70	51.13
23-30	93.80	46.53	50.39
30-41	50.60	19.48	61.50
41-52	62.70	26.62	57.55
52-65	52.70	25.31	51.97
65-72	36.40	19.93	45.24
72-80	23.40	13.91	40.56
80-91	49.50	29.32	40.77
91-100	55.50	35.11	36.74
100-108	108.10	80.83	25.23
108-132	115.40	96.61	16.28

Depth (cm)	LATE SUMMER Wet Weight (g)	 Dry Weight (g)	 % Moisture Content
0-35	62.60	36.06	42.40
35-50	41.80	23.88	42.86
50-65	27.00	12.36	54.22
65-75	46.30	28.16	39.18
75-95	106.20	72.75	31.50
95-115	117.70	80.49	31.61
115-130	137.60	105.53	23.31
130-140	109.40	76.22	30.33
140-155	165.90	134.54	18.90
155-175	149.00	113.12	24.08
175-195	137.30	102.73	25.18
195-205	114.50	70.63	38.31

Appendix A-8: 1997 Soil moisture characteristics of permafrost cores from the Trench treatment, SEEDS, NWT. Sample site was located in the trench on ROW 2 (Coordinates: 35 N-117E). Samples were collected 28 May 1997 and 18 August 1997.

SPRING				LATE SUMMER				TEXTURE				
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-13	11.00	3.31	69.88	**0-15**	9.60	3.92	59.21	**0-13**	14	63	23	10YR 3/2
13-20	45.80	15.03	67.19	**15-35**	37.50	13.77	63.27	**13-20**	16	58	26	10YR 3/3
20-30	74.20	23.88	67.81	**35-52**	81.40	34.60	57.50	**20-30**	17	58	25	10YR 4/1
30-43	59.50	15.66	73.68	**52-65**	49.50	15.96	67.75	**30-43**	15	62	23	10YR 3/3
43-52	43.80	15.93	63.63	**65-75**	98.20	44.55	54.64	**43-52**	18	55	27	10YR 3/3
52-63	76.70	44.87	41.50	**75-85**	104.20	50.92	51.14	**52-63**	15	63	22	10YR 4/2
63-70	59.10	41.09	30.47	**85-100**	180.30	104.72	41.92	**63-70**	20	55	25	10YR 4/3
70-81	99.90	74.45	25.48	**100-112**	97.10	45.71	52.93	**70-81**	15	61	24	10YR 3/2
81-91	103.40	75.55	26.93	**112-120**	144.00	79.06	45.10	**81-91**	22	52	26	10YR 4/3
91-100	126.40	91.02	27.99					**91-100**	13	66	21	10YR 4/3
100-110	124.70	78.42	37.11					**100-110**	17	61	22	10YR 5/2
110-120	99.50	50.53	49.22					**110-120**	16	58	26	10YR 5/2
120-131	136.50	87.45	35.93					**120-131**	19	57	24	2.5Y 6/3
131-140	105.80	75.79	28.36					**131-140**	15	62	23	2.5Y 7/1
140-150	151.20	109.05	27.88					**140-150**	19	60	21	2.5Y 6/3
150-160	153.40	109.64	28.53					**150-160**	14	66	20	10YR 6/2
160-170	120.20	86.29	28.21					**160-170**	17	56	27	10YR 5/3
170-180	152.40	112.37	26.27					**170-180**	15	58	27	10YR 6/3
180-190	140.80	106.28	24.52					**180-190**	18	63	19	10YR 6/3
190-200	123.00	93.51	23.98					**190-200**	21	56	23	10YR 6/2
200-210	162.80	127.16	21.89					**200-210**	19	61	20	10YR 6/2
210-216	97.80	80.33	17.86					**210-216**	20	60	20	10YR 6/3

Appendix A-9: 1997 Soil moisture characteristics of permafrost cores from theROW treatment, SEEDS, NWT. Sample site was located on ROW 2 (Coordinates: 135 N-107E). Samples were collected 28 May 1997 and 18 August 1997.

SPRING					LATE SUMMER		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-12	14.80	6.06	59.07	**0-20**	16.70	4.94	70.40
12-20	36.40	11.99	67.05	**20-40**	83.70	35.46	57.64
20-31	89.90	46.08	48.74	**40-55**	102.00	50.35	50.64
31-41	56.30	27.57	51.03	**55-65**	64.20	31.69	50.65
41-52	156.90	91.35	41.78	**65-85**	116.00	74.40	35.86
52-69	44.50	19.44	56.31	**85-110**	136.20	73.94	45.71
69-80	92.20	53.29	42.20	**110-120**	89.70	50.48	43.72
80-90	102.00	76.39	25.11				
90-101	130.50	94.59	27.52				
101-110	113.70	81.40	28.41				
110-120	112.90	78.11	30.81				
120-130	131.50	95.42	27.44				
130-141	131.30	81.47	37.95				
141-150	99.20	68.83	30.61				
150-160	134.90	99.76	26.05				
160-170	141.20	111.52	21.02				
170-175	117.80	93.83	20.35				

Appendix A-10: 1997 Soil moisture characteristics of permafrost cores from theROW treatment, SEEDS, NWT. Sample site was located on ROW 2 (Coordinates: 40 N-110 E). Samples were collected 28 May 1997 and 18 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-10	33.50	12.98	61.26	**0-15**	10.10	2.41	76.11	**0-10**	19	58	23	10YR 2/3
10-20	74.50	32.96	55.76	**15-25**	58.10	27.95	51.90	**10-20**	18	46	36	10YR 2/1
20-30	90.60	55.30	38.96	**25-55**	84.20	53.68	36.25	**20-30**	20	55	25	10YR 4/3
30-40	93.30	54.48	41.61	**55-65**	114.50	75.97	33.65	**30-40**	13	65	22	10YR 4/2
40-50	81.70	41.69	48.97	**65-95**	156.40	80.77	48.36	**40-50**	16	69	15	10YR 4/2
50-60	101.90	66.34	34.90	**95-100**	146.10	95.08	34.92	**50-60**	17	57	26	10YR 4/3
60-70	86.40	59.41	31.24	**100-110**	79.40	53.32	32.85	**60-70**	21	60	19	10YR 5/1
70-82.5	84.50	53.71	36.44	**110-125**	104.90	71.99	31.37	**70-82.5**	15	68	17	10YR 5/3
82.5-100	123.70	91.83	25.76	**125-135**	98.50	62.26	36.79	**82.5-100**	15	60	25	10YR 6/1
100-110	76.70	65.16	15.05					**100-110**	17	61	22	10YR 6/2
110-120	94.60	79.63	15.82					**110-120**	14	69	17	10YR 6/3
120-130	114.00	87.35	23.38					**120-130**	22	55	23	10YR 6/2
130-140	95.10	65.31	31.32					**130-140**	21	59	20	10YR 6/2
140-151	130.00	96.66	25.65					**140-151**	17	57	26	10YR 6/3
151-160	96.80	71.03	26.62					**151-160**	20	56	24	10YR 6/3
160-171	104.20	79.45	23.75					**160-171**	16	62	22	10YR 6/2
171-180	110.40	85.86	22.23					**171-180**	19	54	27	10YR 6/2
180-193	148.00	119.20	19.46					**180-193**	20	57	23	10YR 6/3
193-200	101.30	84.78	16.31					**193-200**	23	54	23	10YR 6/2

Appendix A-11: 1997 Soil moisture characteristics of permafrost cores from theROW treatment, SEEDS, NWT. Sample site was located on ROW 3 (next to leaf litter site #68). Samples were collected 25 May 1997 and 17 August 1997.

	SPRING				LATE SUMMER		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-12	25.50	13.21	48.21	0-10	2.30	0.97	57.70
12-20	51.90	23.34	55.03	10-23	11.60	5.32	54.16
20-30	86.30	51.51	40.31	23-33	68.70	44.12	35.78
30-40	91.70	53.91	41.21	33-48	116.30	81.44	29.97
40-50	105.60	75.62	28.39	48-60	144.10	102.12	29.13
50-60	112.00	78.63	29.79	60-70	120.50	86.76	28.00
60-70	114.00	83.05	27.15	70-85	54.20	39.99	26.22
70-80	109.10	80.18	26.51	85-90	63.40	45.14	28.80
80-90	103.10	76.05	26.24	90-95	184.80	135.82	26.50
90-100	122.30	96.69	20.94	95-100	70.20	52.34	25.44
100-110	92.40	78.90	14.61				
110-120	118.00	93.70	20.59				
120-130	103.30	72.03	30.27				
130-140	94.70	67.57	28.65				
140-150	125.10	86.82	30.60				
150-160	100.60	73.83	26.61				
160-170	127.90	96.76	24.35				

Appendix A-12: 1997 Soil moisture characteristics of permafrost cores from theROW treatment, SEEDS, NWT. Sample site was located on ROW 3 (next to leaf litter site #37). Samples were collected 25 May 1997 and 17 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-13	32.10	10.15	68.40	**0-20**	11.80	3.56	69.86	**0-13**	20	57	23	10YR 2/1
13-20	40.90	16.93	58.61	**20-40**	27.70	10.16	63.33	**13-20**	19	62	19	10YR 2/2
20-30	65.50	30.50	53.44	**40-60**	29.70	16.73	43.68	**20-30**	17	62	21	10YR 2/2
30-40	82.90	47.23	43.02	**60-75**	139.00	95.13	31.56	**30-40**	21	58	21	10YR 3/2
40-50	121.30	58.97	51.38	**75-90**	146.00	107.67	26.25	**40-50**	20	58	22	10YR 3/4
50-62	112.20	67.32	40.00	**90-115**	132.60	95.98	27.62	**50-62**	18	58	24	10YR 3/4
62-82	206.70	130.04	37.09	**115-130**	109.20	78.05	28.53	**62-82**	21	58	21	10YR 3/4
82-91	74.80	51.32	31.39	**130-145**	165.20	127.13	23.04	**82-91**	23	57	20	10YR 4/3
91-104	101.40	74.55	26.48	**145-165**	143.90	106.80	25.78	**91-104**	19	63	18	10YR 4/3
104-113	62.20	47.17	24.16	**165-190**	162.40	124.85	23.12	**104-113**	16	65	19	10YR 4/1
113-120	48.20	33.18	31.16	**190-205**	145.10	107.34	26.02	**113-120**	18	61	21	7.5YR 5/1
120-130	60.10	48.53	19.25	**205-217**	98.40	73.82	24.98	**120-130**	18	62	20	7.5YR 5/1
130-145	130.30	101.33	22.23					**130-145**	20	57	23	7.5YR 4/2
145-160	67.30	46.80	30.46					**145-160**	20	59	21	10YR 5/2

Appendix A-13: 1997 Soil moisture characteristics of permafrost cores from the Trench treatment, SEEDS, NWT. Sample site was located in the trench on ROW 3 (next to leaf litter site #37). Samples were collected 25 May 1997 and 17 August 1997.

	SPRING				LATE SUMMER		
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content
0-10	67.40	29.81	55.78	**0-10**	11.20	1.63	85.45
10-24	108.30	55.54	48.72	**10-23**	16.60	3.98	76.00
24-30	44.90	20.24	54.93	**23-35**	38.80	15.79	59.30
30-40	72.30	35.22	51.29	**35-50**	69.30	37.59	45.76
40-50	86.50	48.38	44.07	**50-70**	116.20	72.82	37.33
50-60	117.10	66.96	42.82	**70-90**	119.00	74.04	37.78
60-72	131.30	77.44	41.02	**90-110**	135.50	100.26	26.01
72-80	68.20	47.32	30.62	**110-123**	92.40	59.70	35.39
80-93	106.10	72.01	32.13	**123-140**	168.10	126.14	24.96
93-100	45.30	34.03	24.87	**140-168**	145.70	112.56	22.75
100-110	52.00	39.89	23.29	**168-190**	121.80	88.14	27.64
110-120	61.90	51.08	17.47	**190-205**	111.70	79.36	28.95
120-130	70.80	57.97	18.13	**205-210**	52.80	41.24	21.89
130-155	126.70	97.41	23.12				
155-160	77.40	55.94	27.73				
160-170	60.60	44.61	26.38				
170-180	75.80	51.82	31.64				
180-190	45.90	30.05	34.53				

Appendix A-14: 1997 Soil moisture characteristics of permafrost cores from the Trench treatment, SEEDS, NWT. Sample site was located in the trench on ROW 3 (next to leaf litter site #68). Samples were collected 26 May 1997 and 17 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-15	33.40	8.68	74.02	**0-16**	14.30	3.87	72.93	**0-15**	32	53	15	10YR 3/3
15-20	49.60	20.94	57.79	**16-28**	67.80	39.48	41.77	**15-20**	33	47	20	10YR 4/3
20-40	109.80	60.47	44.93	**28-40**	141.40	93.12	34.14	**20-40**	28	55	17	2.5Y 4/4
40-50	88.70	57.37	35.32	**40-60**	149.60	111.04	25.78	**40-50**	29	52	19	2.5Y 4/2
50-60	85.60	65.43	23.56	**60-75**	157.10	122.88	21.78	**50-60**	34	44	22	10YR 4/2
60-70	95.30	79.05	17.05	**75-85**	167.60	130.46	22.16	**60-70**	26	60	14	10YR 4/2
70-80	96.60	83.19	13.88	**85-100**	148.50	107.35	27.71	**70-80**	32	50	18	2.5Y 5/2
80-90	94.70	80.45	15.05	**100-110**	71.20	51.46	27.72	**80-90**	30	55	15	2.5Y 5/4
90-100	106.10	96.18	9.35	**110-130**	114.00	81.75	28.29	**90-100**	37	42	21	2.5Y 7/4
100-110	179.60	160.89	10.42					**100-110**	19	65	16	10YR 6/3
110-114	126.30	114.68	9.20					**110-114**	28	57	15	10YR 6/3

Appendix A-15: 1997 Soil moisture characteristics of permafrost cores from the Control treatment, SEEDS, NWT. Sample site was located 11 m east of the microclimate station. Samples were collected 26 May 1997 and 10 August 1997.

	SPRING				LATE SUMMER				TEXTURE			
Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Colour
0-12	40.30	22.16	45.01	**0-20**	26.90	15.20	43.51	**0-20**	19	65	16	10YR 3/2
12--20	33.70	17.28	48.72	**20-40**	121.50	91.61	24.60	**20-40**	22	61	17	10YR 3/2
20-30	104.40	73.74	29.37	**40-60**	149.00	118.31	20.60	**40-60**	18	68	14	10YR 3/3
30-40	71.80	58.91	17.96	**60-70**	164.50	131.26	20.21	**60-70**	19	70	11	10YR 3/3
40-50	100.00	89.38	10.62	**70-80**	142.80	95.85	32.88	**70-80**	21	60	19	2.5Y 5/2
50-60	187.30	171.13	8.63	**80-100**	161.00	128.74	20.04	**80-100**	23	56	21	10YR 6/3
60-71	158.30	147.36	6.91	**100-110**	105.30	82.40	21.75	**100-110**	20	62	18	10YR 6/3
71-80	114.80	106.71	7.05	**110-115**	96.90	77.61	19.91	**110-115**	28	50	22	10YR 6/3
80-90	95.20	86.83	8.79	**115-120**	74.40	59.96	19.40	**115-120**	26	55	19	10YR 5/2
90-94	126.30	116.24	7.97	**120-125**	55.10	41.72	24.28	**120-125**	27	54	19	10YR 5/2

Appendix A-16: 1997 Soil moisture characteristics of permafrost cores from the Control treatment, SEEDS, NWT. Sample site was located 23 m west of the microclimate station. Samples were collected 26 May 1997 and 10 August 1997.